Modernizing the NWS Tropical Cyclone Product Suite by Evaluating NWS Partner Decisions and Information Needs,

Part 1: Interviews with Broadcast Meteorologists and Emergency Managers

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ABSTRACT

As tropical cyclone threats evolve, broadcast meteorologists and emergency managers rely on timely forecast information to help them communicate risk with the public and protect public safety. This study aims to improve the usability and applicability of NWS forecast information in the context of these NWS core partners' decisions and activities during tropical cyclone threats. The research collected and analyzed data from in-depth interviews with broadcast meteorologists and emergency managers in three coastal U.S. states. These data were used to analyze broadcast meteorologists' and emergency managers' tropical cyclone decision and action timelines, their use of tropical cyclone information during different phases of threats, and gaps in forecast information for decision making. Based on these findings, several opportunities for improving tropical cyclone risk communication were identified. Recommendations to address gaps in the NWS tropical cyclone product suite include designing improved ways to communicate storm-specific storm surge risk at greater than 48 hours of lead time, expanding the use of concise highlights that help people quickly extract and understand key information, and improving product understandability and usability by more comprehensively integrating users' perspectives into product research and development. Broader strategic recommendations include developing new approaches for informing broadcast meteorologists about major forecast updates, presenting forecast information in ways that enable locally relevant interpretation, and supporting human forecasters' contributions to the effectiveness of NWS products and services. These findings and recommendations can help NOAA prioritize ways to modernize the current NWS tropical cyclone product suite as well as motivate research to enable longer-term high-priority improvements.

1. INTRODUCTION

When a tropical cyclone[1] (TC) threatens the United States, broadcast meteorology and emergency management professionals act as key partners to NOAA's National Weather Service (NWS) in communicating the complex forecast information available and translating that information into protective actions. Although the NWS originates much of the weather forecast and warning information available in the United States, most members of the public access TC and other weather forecast information from non-NWS sources, including broadcast meteorologists (Lazo et al. 2009, Milch et al. 2018, Sherman-Morris et al. 2020). Using information from the NWS and other sources, emergency managers play critical roles in informing people about approaching TC risks and making community preparation and response decisions (Demuth et al. 2012, Bostrom et al. 2016). Together, these groups provide a foundation for the TC forecast and warning system, whose broader common goals include saving lives and reducing property loss and other harm (Mileti and Sorensen 1990, Gladwin et al. 2007, Lindell et al. 2007, Demuth et al. 2012, Bostrom et al. 2016).

Given the societal importance of these goals, there is a national imperative for modernizing the weather forecast and warning system in ways that take into account evolving technologies, practices, and societal needs. This study aims to help fulfill this imperative by supporting NOAA's efforts to improve its TC risk communication with these key partner groups. In particular, we investigate how, over the shorter and longer term, NOAA can improve the collection of TC forecast and warning products, information, and services provided by the NWS, referred to as the *TC product suite* (NOAA 2019). To do so, we address three research questions:

- **RQ1**: What are broadcast meteorologists' and emergency managers' primary decisions and actions during different phases of TC threats?
- **RQ2**: What NWS TC products and other TC information do broadcast meteorologists and emergency managers use in different phases of threats?
- **RQ3**: What are broadcast meteorologists' and emergency managers' key unmet needs related to TC forecast and warning information?

Although a few previous studies have examined TC warning system professionals (see section 2), the creation, communication, and use of information is changing rapidly with new technologies (Morss et al. 2017), and so updated, more in-depth understanding is needed.

We investigate these questions using data collected from semi-structured interviews with 20 broadcast meteorologists and emergency managers in coastal and inland areas of the United States affected by TCs, combined with a review of relevant literature. Our aim is to evaluate the TC product suite from a forward-looking perspective, using a decision- and user-centered approach (Argyle et al. 2017; Demuth et al. 2020). Thus, in addition to asking interviewees about their perspectives on the current TC product suite, we analyze their TC information needs more broadly by investigating their decision and action timelines during TC threats and the current and potential future intersections of TC forecast and warning information with those timelines. We then use the in-depth knowledge gained to identify key information gaps and develop research-

[1] In this document, we use the general term "tropical cyclone" to include a variety of types of tropical cyclones that may pose threats to the United States, including hurricanes.

guided recommendations. This includes recommended priorities for modernizing the TC product suite over the next few years, as well as strategic recommendations for longer-term investments in TC forecasting and risk communication. Our research team collaborated with a core team of NOAA Research and NWS personnel[2] to develop the study approach, design the methodology, and translate the findings into usable recommendations.

Note that a shorter version of this report is available in the form of a journal publication (Morss et al. 2022c). An additional goal of the interviews was to build foundational knowledge for designing and implementing surveys with larger, more systematic samples of broadcast meteorologists and emergency managers, to gather a broader range of perspectives for evaluating the TC product suite and prioritizing improvements (Bostrom et al. 2022; Morss et al. 2022b). The knowledge gained from this study also contributes to the literature in hazard risk communication, decision making, and warning systems.

After providing an overview of relevant literature and the study framing in section 2, we describe the interview data collection and analysis process in section 3. Sections 4 and 5 present findings pertaining to research questions 1 and 2 above, including broadcast meteorologists' and emergency managers' decision and action timelines, their key information needs within those timelines, and their use of different types of TC information. Section 6 addresses research question 3, highlighting key information gaps and recommendations identified by our analysis, followed by a concluding section.

[2] This core NOAA team included the NWS Tropical Services Program Leader, an NHC Hurricane Specialist, and additional NWS staff, as well as staff in the Weather Program Office's Social Science Program and the Atlantic Oceanographic and Meteorological Laboratory within NOAA's Office of Oceanic and Atmospheric Research.

2. BACKGROUND AND STUDY FRAMING

The literature on how members of the public interpret and respond to TC forecasts and warnings has grown rapidly over the last decade. Fewer studies, however, have focused on hurricane warning system professionals. As part of our study, we reviewed relevant published and "gray" literature[3] on broadcast meteorologists' and emergency managers' information use and decisions during TC threats, summarized in this section. Key concepts, findings, and recommendations from the literature were then incorporated into the interview guide and data analysis.

Prior research on U.S. emergency managers during TCs includes empirical studies of emergency managers and emergency management plans (e.g., Urbina and Wolshon 2003, Wolshon et al. 2005, Demuth et al. 2012, Losego et al. 2012, Bostrom et al. 2016, Hoekstra and Montz 2017a,b) as well as experimental studies with non-emergency managers playing emergency management roles (e.g., Wu et al. 2015, Huang et al. 2017). This research also includes studies of how emergency managers could or should make evacuation decisions, using simplified decision modeling or evacuation modeling and decision support systems (e.g., Lindell and Prater 2007, Trainor et al. 2012, Dye et al. 2014, Gudishala and Wilmot 2017, Davidson et al. 2018). Much of this previous research focuses on emergency managers' evacuation order[4] decisions, which are one of the most visible ways that they help protect public safety during such threats. Evacuation orders are important because, for some members of the public at risk from an approaching TC, they are a major motivator for taking protective action (e.g., Gladwin et al. 2001, Lazo et al. 2015, Demuth et al. 2018). Depending on the situation, emergency managers may make evacuation order decisions or provide advice to elected officials making those decisions. One particular emphasis in previous research is the timing of general population evacuation orders, because it is challenging to issue evacuation orders for as few areas as possible, but far enough in advance to enable everyone at risk to get to safety, given clearance times[5] and forecast uncertainties.

By providing a more in-depth understanding of emergency managers' decision-making processes, our work can inform decision modeling research and the development of decision support systems focused on evacuation orders. Complementing prior research focused around evacuation order decisions, it is also important to develop process-oriented understandings of a broader range of emergency managers' decisions and actions during TC threats. This includes additional knowledge about the decisions that lead up to and follow evacuation orders, and the information used to inform those decisions, across a variety of jurisdictions and TC situations. To help address this knowledge gap, we interviewed emergency managers working in different types of jurisdictions in two U.S. regions about their information use, decisions, and actions

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[3] Types of literature reviewed include relevant peer-reviewed journal articles, book chapters, master's theses and PhD dissertations, conference publications, state and local hurricane plans, FEMA and NOAA training modules and presentations, and other agency-generated and agency-sponsored reports.

[4] Depending on the location and situation, these can include mandatory evacuation orders, voluntary evacuation orders, and other types of evacuation recommendations; here, we refer to these collectively as evacuation orders.

[5] Clearance time refers to "the number of hours it takes to move the threatened population to safety given various factors such as the category of storm, the tourist occupancy (or population) of the area at the time, and public responsiveness" (National Hurricane Program 2021).

throughout the life of TC threats. In this way, we approach their evacuation order decisions as part of their larger risk assessment and public safety coordination process, in the context of evolving forecast information and decision making (Wolshon et al. 2005, Morss and Ralph 2007, Bostrom et al. 2016, Morss et al. 2017, Hoekstra and Montz 2017b).

Many state and local emergency plans contain recommended guidelines and schedules for emergency management decisions during TC threats (Urbina and Wolshon 2003, Wolshon et al. 2005, FEMA 2013, Gudishala and Wilmot 2017, National Hurricane Program 2017), and these inform our work. However, TCs, their forecasts, and their potential impacts all vary widely from situation to situation, and TC risk management requires dealing with complex, intersecting uncertainties. Consequently, making or advising protective decisions during real hazard threats requires judgement and discretion, and such decisions can vary significantly within general established procedures (Wolshon et al. 2005, Hoekstra and Montz 2017a, Morss et al. 2022a). Moreover, emergency managers update their decision processes as forecasts improve, enabling longer-lead-time decisions, and as best practices and other influencing factors change. Our study therefore seeks to understand emergency managers' current perspectives on their actual decision timelines and priority forecast information needs, complementary to written hurricane emergency plans and research on how emergency managers could and should make decisions leading up to a TC.

Compared to emergency managers, there have been fewer studies of broadcast meteorologists during TCs. Daniels and Loggins (2007) and Prestley et al. (2020) investigated how television meteorologists communicate with the public during TC threats, but they did not examine the research questions of interest here, and they focused primarily on high-impact periods near landfall. Other research has examined broadcast meteorologists together with emergency managers and NWS forecasters in the context of their roles and interactions within the TC warning system (Demuth et al. 2012, Anthony et al. 2014, Bostrom et al. 2016). This prior research noted the importance of effective coordination among warning system actors, as well as the tensions and tradeoffs of managing uncertainties. It therefore recommended further efforts to "evaluate, test, and improve the NWS product suite through collaborations among warning system partners and with social scientists" (Demuth et al. 2012, p. 1142) and to "improve coordination within the system, with an eye toward creating a more streamlined and effective [NWS] product portfolio" (Bostrom et al. 2016, p. 126), which our current study helps fulfill.

This study's examination of the NWS TC product suite also builds on prior work to understand and improve how broadcast meteorologists and emergency managers interpret and use specific NWS TC forecast and warning products (e.g., Losego et al. 2012, Hogan Carr et al. 2016, Morrow et al. 2015). Key findings from this research, along with the TC warning system research discussed above, include the importance of developing NWS products that are more easily understandable, visually appealing, and locally relevant. In addition, multiple studies have found that emergency managers would like to receive some types of TC forecasts and warnings earlier, particularly storm surge and flooding products (Safford et al. 2006, Losego et al. 2012, Morrow and Lazo 2014, Hogan Carr et al. 2016, Hoekstra and Montz 2017b, Munroe et al. 2018). Here we explore whether these product improvements are still priorities given recent changes to the NWS product suite, and we provide decision-focused evidence documenting broadcast meteorologist and emergency manager needs for modernizing the TC product suite as a whole.

3. METHODS

This study focused on broadcast meteorologists and emergency managers because of their essential, sustained roles in fulfilling the NOAA and NWS missions when a TC threatens the United States. As depicted in Figure 3 of Uccellini and Ten Hoeve (2019), broadcast meteorologists are *core partners* to the NWS, i.e., "government and non-government entities who are directly involved in the preparation, dissemination, and discussions involving National Weather Service information that supports decision making," and emergency managers are *deep relationship core partners*, i.e., a subset of core partners that includes "government officials responsible for public safety" (p. 1931; see also NWS 2018). Within the broader weather enterprise, which also includes academia and others in private industry, government, and non-governmental organizations (NWS 2019, p. 6), broadcast meteorologists and emergency managers serve as vital conduits between the NWS and other core partners, general partners, and members of the public, helping "amplify NWS's message" and its influence on decision making (Uccellini and Ten Hoeve 2019, p. 1931). Thus, input from these groups is critical for making decisions about modernizing the TC product suite, complementing other recent and ongoing social and behavioral science research.

3.1. Interview Sample and Implementation

The results presented here are based on data collected from 17 in-depth interviews with 20 participants[6] in Georgia, South Carolina, and southeastern Texas, as shown in Table 1. We selected these geographical areas in collaboration with NOAA to represent two different TC-prone regions of the United States (the Gulf Coast and the southeastern U.S. Atlantic Coast) in terms of TC risks and vulnerabilities, recent TC experiences, and social and cultural factors. Within the southeastern United States, we conducted interviews in both Georgia and South Carolina to incorporate perspectives associated with the different structures for evacuation order decision making in the two states: in South Carolina, the state governor has sole authority, whereas in Georgia this authority resides at both the state and local levels (Urbina and Wolshon 2003). In Texas, local elected officials have sole authority to declare evacuation orders. Interviews were conducted in both coastal and non-coastal communities, in a mix of metropolitan and less-populated areas, consistent with our goal of developing foundational knowledge that could be used to design surveys relevant to broader samples of broadcast meteorologists and emergency managers in the Atlantic TC basin. Our initial study plan included interviews in a third region, the New York / New Jersey area, but we were unable to conduct these interviews due to the COVID-19 pandemic as explained below.

The broadcast meteorologist interviewees worked at local television stations in either a Chief Meteorologist or Morning Meteorologist role. Interviewees' job roles during TC threats included interpreting and developing forecast content, communicating with their audiences on television and other platforms, communicating with the NWS and other external partners, and helping coordinate event coverage and emergency planning within their organization. Their experience in this type of job ranged from 10 to more than 30 years.

[6] Fourteen interviews had one interviewee, and three interviews had two interviewees.

Emergency manager interviewees worked in full-time job roles such as public safety director, emergency management coordinator, or district coordinator, with jurisdictions at the city, county, regional (within state), or state level. Their primary job responsibilities included emergency management oversight in day-to-day and emergency operations; cross-agency coordination; and response, mitigation, and recovery planning. During TC threats, their job roles included communicating TC information and raising situational awareness in their organization, making or coordinating emergency management decisions, communicating with the media or members of the public, and interacting with elected government officials. Their experience in this type of job ranged from 6–50 years.

Table 1. Number of broadcast meteorologist and emergency manager interviewees by state.

State	Broadcast Meteorologists (n=7)	Emergency Managers (n=13)
Georgia	n=3	n=5
South Carolina	n=2	n=2
Texas	n=2	n=6

The interviews were conducted in February and early March 2020, with 10 taking place in person and 7 over the phone.[7] Several additional interviews in the two sampled regions were planned, as well as interviews in a third region as noted above. However, the rapidly evolving COVID-19 pandemic created difficulties for recruiting additional interviewees and scheduling interviews, forcing us to stop interview data collection in mid-March 2020. The interviews lasted 45–120 minutes (median of 66 minutes). Each interview was audio recorded and professionally transcribed for analysis.

3.2. Interview Guide

The interview guide (Appendix 1) was developed by the research team in partnership with NOAA collaborators. Many of the questions were adapted from previous work to understand professionals' decision processes and forecast information use for TCs and other weather-related hazards (Demuth et al. 2012; Morss et al. 2015, 2022a; Bostrom et al. 2016). Prior to conducting the interviews used in the analysis, the guide was pretested with one broadcast meteorologist and one emergency management professional, and then revised based on the pretests.

The interview guide began with questions about interviewees' job roles and experience. The second section of the interview focused on interviewees' decisions and forecast information use during evolving TC threats. To frame the interview questions and encourage interviewees to discuss a variety of TC situations, we asked them to talk about a variety of types of TC threats or events, ranging from a tropical depression or tropical storm to a Category 5 hurricane, along with different types of associated hazardous conditions such as extreme winds, storm surge, heavy rainfall, inland flooding, rough surf, rip currents, and tornadoes. To guide interviewees through talking about different stages of threats, they were asked about their decisions and actions,

[7] This research was approved by the University Corporation for Atmospheric Research Human Subjects Committee.

forecast information use and sources, and recommendations for improved forecast information during each of three phases of TC threats: 1) from when they first become aware of a threat until about 5 days out from when a storm is expected to affect their area, 2) from about 5 days to 48 hours out, and 3) from about 48 hours out until landfall or impacts. These three time frames were selected based on the literature review and the pretests; we invited interviewees to adjust the time frames based on what made sense in their job context, but none did so. We then asked interviewees about exceptions to their typical TC timeline, information they use about specific TC hazards, individuals or communities in their region that are particularly vulnerable to TCs, and management of uncertainties and inconsistencies in forecast information and decision making.

In the final section of the interview, interviewees were presented with the set of twelve NWS TC product examples shown in Figure 1 and asked which they use, which they find most useful, and why. We selected this set of products, with guidance from our NOAA collaborators, to represent different types of key forecast and warning information within the NWS TC product suite, across the lifetime of a TC threat. It includes TC-related products issued by three national NWS entities—the National Hurricane Center (NHC), Weather Prediction Center (WPC), and Storm Prediction Center (SPC)—as well as local NWS Weather Forecast Offices (WFOs), which focus on a multi-county area of responsibility.[8] We then asked interviewees about possible improvements to the product suite and additional TC forecast information they would like to have. In asking these questions, our aim was not to get in-depth feedback about each product, but rather to hear interviewees' perspectives about the TC product suite *as a whole*.

3.3. Interview Data Coding and Analysis

The qualitative coding and analysis were performed in NVivo, with the goal of integrating project-driven objectives with data-driven insights. First, 2 members of the research team read through all 17 interview transcripts and designed an initial hierarchical coding scheme that combined key concepts in the interview questions and project goals with those mentioned by interviewees. The coding scheme included code definitions, along with directions for marking excerpts and concepts of interest within the transcripts. Two researchers then tested and refined the coding scheme and assessed inter-coder reliability by independently coding and comparing four transcripts (two broadcast meteorologist and two emergency manager transcripts from different regions) in two stages. For the initial two transcripts, the researchers coded independently and then went through the transcripts line by line to compare coding, discuss discrepancies, and clarify code definitions and coding instructions. The researchers then independently coded the following two transcripts using the revised coding scheme and ran the coder comparison query in NVivo to evaluate inter-coder reliability.

[8] NHC focuses on hazardous tropical weather, including TCs; its TC track, intensity, and size forecasts underpin most TC hazard forecast and warning information generated by NHC itself (e.g., the Storm Surge Unit), other NWS national prediction centers, and WFOs. In the context of TCs, WPC and SPC provide information focused on TC-related hydrometeorological (e.g., heavy rainfall) and convective (e.g., tornado) hazards, respectively. WFOs provide more localized weather products and information focused on their area of responsibility.

TC product	Product source	Product description
Graphical Tropical Weather Outlook	NWS National Hurricane Center	Map depicting the TC formation potential of current and future tropical disturbances during the next 2 or 5 days.
Track Forecast Cone (“Cone of Uncertainty”)	NWS National Hurricane Center	Map depicting the probable track of the center of a TC during the next 5 days, along with its forecasted intensity, watches/warnings, and other information.
Tropical Cyclone Wind Speed Probabilities Graphic	NWS National Hurricane Center	Map depicting the probability of sustained surface winds of at least 39 mph (tropical storm), 58 mph, or 74 mph (hurricane) at different locations during the next 5 days.
Arrival of Tropical-Storm-Force Winds Graphic	NWS National Hurricane Center	Map depicting the forecasted Earliest Reasonable or Most Likely time of onset of sustained 39 mph winds at different locations during the next 5 days.
Key Messages Graphic	NWS National Hurricane Center	Graphic with text highlights about a TC’s forecast and hazards, along with relevant NWS graphical TC products.
Tropical Cyclone Public Advisory	NWS National Hurricane Center	Text product containing a list of all current watches and warnings for a TC, along with the storm’s position, current motion, intensity, and other information.
Potential Storm Surge Flooding Map	NWS National Hurricane Center	Map depicting the risk of coastal flooding from storm surge at different land locations, issued within 48 hours of anticipated impacts along the U.S. coast.
Storm Surge Watch/ Warning Graphic	NWS National Hurricane Center	Map depicting areas where there is a possibility (watch) or danger (warning) of life-threatening storm surge in the next 48 or 36 hours, respectively.
Excessive Rainfall Outlook Graphic	NWS Weather Prediction Center	National map depicting the risk of potentially flooding rainfall at different locations during the time indicated (e.g., Day 1, Day 2, Day 3).
Convective Outlook Graphic	NWS Storm Prediction Center	National map depicting the risk of severe convective weather at different locations during the time indicated (e.g., Day 1, Day 2, Day 3).
Hurricane Local Statement	NWS Weather Forecast Offices	Text product containing a list of watches/warnings, potential hazardous conditions and impacts, and other information about a TC for a local area.
Hurricane Threats and Impacts Graphics	NWS Weather Forecast Offices	Set of regional maps depicting the risk of TC-related hazardous wind, storm surge, flooding rain, and tornadoes at different locations, issued within 48 hours of anticipated impacts in the region.

Figure 1. NWS TC-related products presented to interviewees. Product descriptions were obtained from NOAA via noaa.gov and weather.gov. A version of the figure with examples of each product is provided in Appendix 2.

The coding scheme included 67 codes: 59 sub-codes within 4 high-level codes (*Decisions and actions*,[9] *Forecast and other meteorological information*, *TC hazards and characteristics*, and *TC time frame*) and 4 additional codes (*At-risk populations*, *Public messaging and decision*

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[9] We phrased the interview questions in terms of decisions and actions and kept these together in the coding scheme because in some cases interview pre-testers and interviewees discussed the actions they take at different times corresponding to their decisions, rather than explicitly referencing the decisions they make that lead up to those actions.

making, *Job roles*, and *Miscellaneous*). Eleven of these 67 were either inferential codes designed to mark excerpts for later analysis of latent constructs (Miles and Huberman 1994) or codes used for marking miscellaneous content not listed in the coding scheme; the remaining 56 codes were used to evaluate inter-coder reliability at the paragraph level, with sub-codes aggregated to higher-level codes. Cohen's kappa was 0.8 or higher for 34 (61%) of these codes, and between 0.65 and 0.8 for an additional 9 codes (16%). The only codes with kappa≤0.5 were used 5 or fewer times by the 2 coders. The full coding scheme and inter-coder reliability results are provided in Appendix 3.

After assessing inter-coder reliability, the researchers discussed and addressed discrepancies, with a focus on clarifying the definitions of codes that had lower inter-coder reliability or had been used few times. Next, the final coding scheme was used by one researcher to adjudicate the 4 cross-coded transcripts and code the remaining 13 transcripts. We then systematically analyzed the interview data by compiling excerpts associated with different codes, synthesizing findings, and capturing themes pertaining to the project objectives. Most excerpts were coded with multiple codes, ensuring that key data were viewed multiple times during the analysis process, from different perspectives. To illustrate key points, we use anonymized quotes[10] accompanied by an identifier indicating the interviewees' job type (EM/BR), location (TX/SC/GA), and interview order (for example, BRTX1, or EMTX4&5 for an interview with two participants).

Although sometimes interviewees specified which NWS entity they were obtaining information from, often they discussed NWS more generally. They also sometimes referred to obtaining information or products generated by one NWS entity in the context of another NWS entity, for example, by discussing information that is typically originated by a national center in the context of communication with a local office. For these reasons as well as our focus on the NWS TC product suite as a whole, much of the paper refers to NWS forecast information and products more generally rather than information from specific groups within the NWS. This approach is consistent with the NWS's emphasis in recent years on improving coordination and consistency of forecast and warning messaging across the organization (NWS 2019, Uccellini and Ten Hoeve 2019).

[10] Quotes are verbatim, except for removal of filler words such as "like" or "umm."

4. NWS PARTNER DECISION AND ACTION TIMELINES

To address the first research question, this section analyzes broadcast meteorologists' and emergency managers' decisions and actions during three phases of TC threats: 1) monitoring and awareness, 2) readiness and action, and 3) transition to impacts and response. These phases, summarized in Figure 2, were distilled from the interview data across both groups and relevant previous literature. They mirror the three time frames used in the interview guide, but we discuss them in terms of decision and action themes rather than time periods because the specific time frames for decisions can vary depending on the evolution of the storm and its forecasts as well as other factors. These phases are consistent with emergency management timelines in hurricane plans and previous related research (see, e.g., Morss and Ralph 2007, Gudishala and Wilmot 2017, Hoekstra and Montz 2017b), adapted to reflect current TC forecast skill and decision processes and to provide a more general framework that is common across the different NWS partners we studied and types of TC situations they may experience.

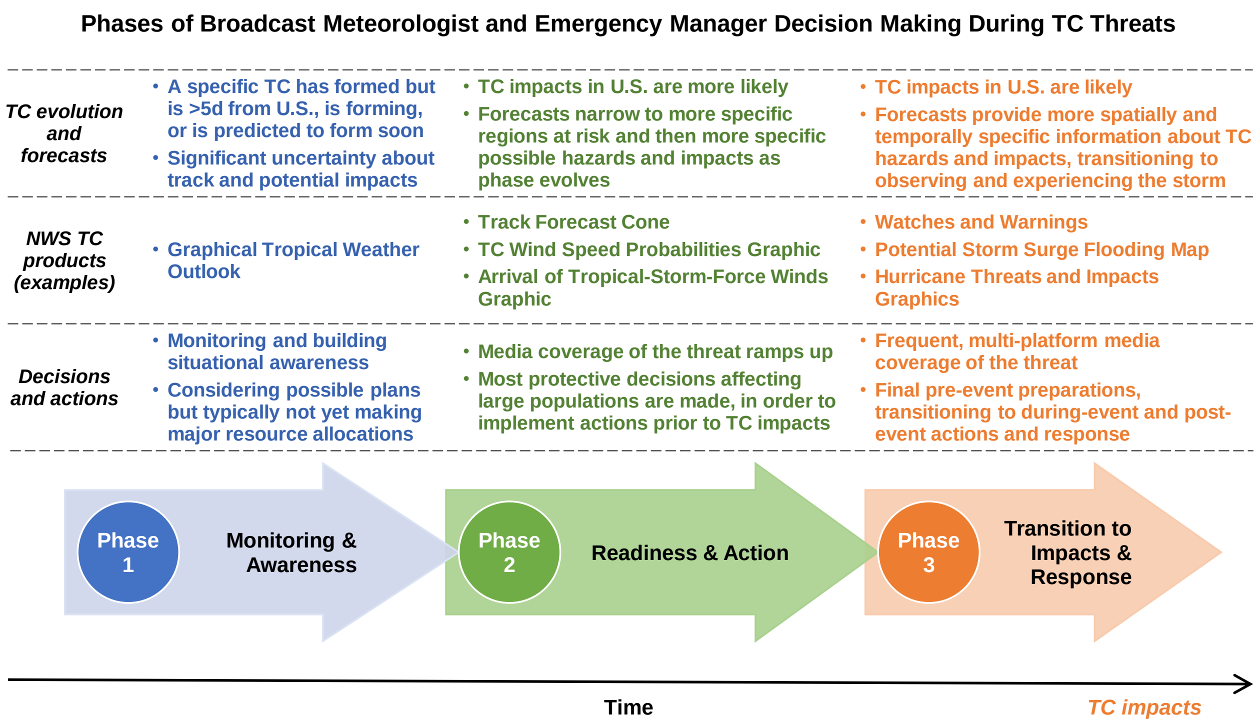

Figure 2. Overview of the three phases in the NWS partner decision and action timelines, including the characteristics of TCs and their forecasts, example NWS TC products, and a synthesis of decisions and actions that are typical within each phase. Note that the timeline is not absolute, but relative to anticipated TC impacts in a given decision-maker's jurisdiction. In other words, different NWS partners may be in different phases at the same time.

The phases in Figure 2 are framed with respect to arrival of TC impacts[11] rather than landfall for several reasons. First, as discussed below, arrival of TC impacts represents a shift in activities for both groups we studied—especially for emergency managers, who indicated that a key driver of

[11] When discussing arrival of TC impacts, interviewees most frequently discussed arrival of tropical storm force winds. However, in some situations, storm surge inundation can precede hazardous winds.

their timelines was completing preparations prior to the arrival of TC conditions that will threaten the safety of their own personnel and others outside or in vehicles.[12] Second, broadcast meteorologists and emergency managers take actions if a TC may cause significant impacts in their jurisdiction, even if it is anticipated to make landfall far from their region or not make landfall in the United States. Thus, this framing makes the timeline relevant for a wider range of regions and storms (e.g., inland areas, TCs that parallel the coast or make multiple landfalls).

Depending on the storm, the first phase can be short or last for many days. With current forecast skill, the second phase typically begins about 5 days before TC impacts, and the third phase about 48 hours before impacts. However, these phases can begin earlier or later depending on the forecast uncertainty and how close to the United States a TC forms or significantly intensifies. The time frames corresponding to the three phases are also determined in part by current predictive capabilities for TCs and the associated availability of different NWS TC products at different times; consequently, the time frames for decision making have shifted as forecasts have improved.

These timelines and associated descriptions are for those in locations that continue to be at risk (and then are impacted) as a TC approaches. Others may start in the first phase of the timeline but then shift to other activities as the area at risk narrows and no longer includes their location.

4.1. Broadcast Meteorologist Decision and Action Timeline

Broadcast meteorologists discussed three intersecting types of activities that they engage in during TC threats: information gathering and interpretation, communication and engagement with public audiences, and communication and preparation within their station (and, if relevant, its parent organization). An overview of these activities in different phases of TC threats is provided in Figure 3, and illustrative quotes are provided in Figure 4.

Across the timeline, broadcast meteorologists' information-gathering and interpretation activities focused on receiving and seeking TC-related information from the NWS and other sources, and comparing and interpreting the information to pick up on trends and to synthesize key aspects of TC threats. They do so using software from private sector vendors (e.g., The Weather Company / WSI) that enables them to access and process NWS data and create graphics, as well as in other ways for information accessed outside their vendor platforms. Broadcast meteorologists use this information to provide media coverage of evolving threats, in other words, to communicate about TC threats with viewers and other audiences through multiple media platforms, including television, station websites and apps, and social media (e.g., Twitter, Facebook). Because in most situations they convey information visually as well as verbally, much of their communication involves graphics, especially graphics adapted from NWS products or designed in house using NWS and other data. They communicate using both still and animated graphics, often accompanied by verbal explanations. Internally, they communicate and collaborate with

[12] Some emergency managers we interviewed discussed their decisions in terms of operating conditions (OPCONs), which are pre-specified alert levels defined in their emergency plans, or decision points in their timelines in terms of hours to evacuation (E-hours) or TC impacts (H-120). However, all emergency managers explained that their decision and action timelines are built around the arrival of TC impacts (not landfall).

meteorological and news personnel and management at their organization to make decisions about how to cover the situation and make emergency preparations for their station.

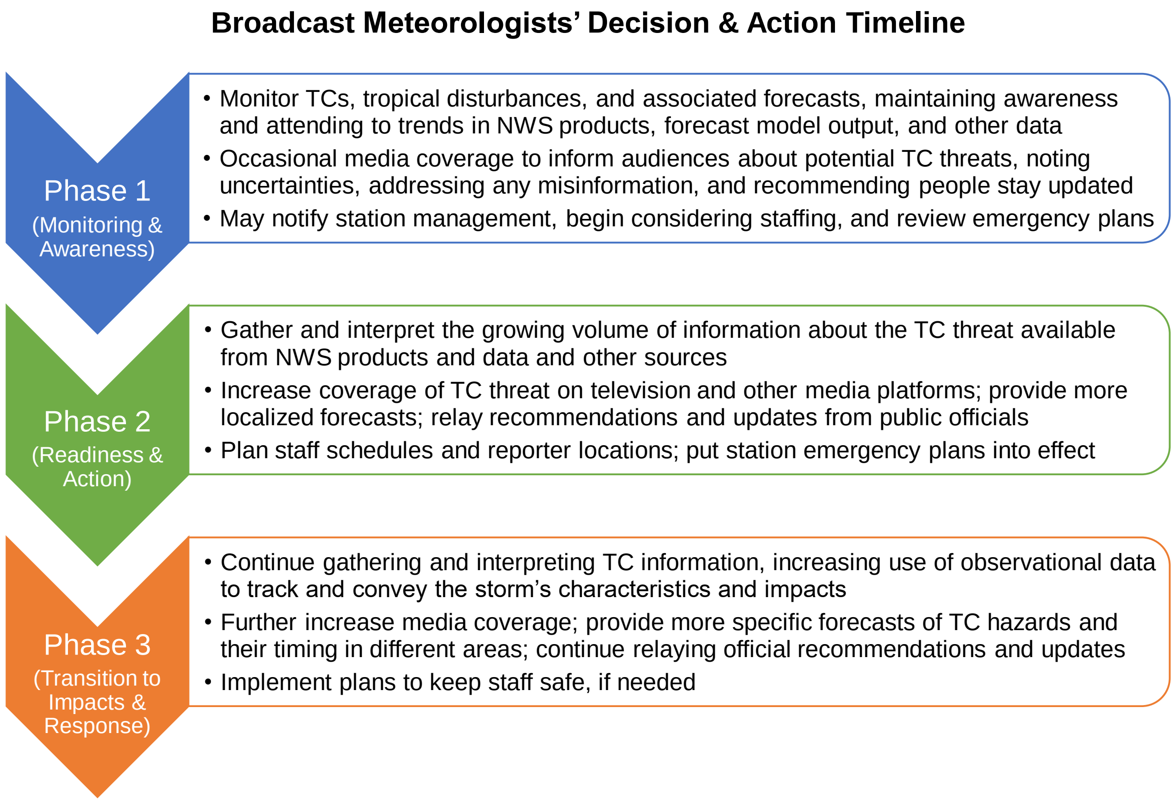

Figure 3. Overview of broadcast meteorologists' major decisions and actions during TC threats, for each of the three phases in the timeline depicted in Figure 2. Additional information about each of the activities shown is provided in section 4.1, and illustrative quotes for each phase are provided in Figure 4.

Broadcast meteorologists explained that their primary goals during TC threats are to provide audiences with clear, accurate, credible information that is consistent across shifts and station personnel, and to tell people to remain aware and prepared. Within the weather community, concerns have been raised about broadcast meteorologists conveying information differently for marketing and branding reasons (Williams and Eosco 2021). However, many interviewees said that they aim to provide forecast information that is consistent with official NWS sources so as not to create divergent or inconsistent messaging that may cause confusion. For example, one described how he looks at NWS briefings and other information and consults with the local NWS office to "try to relay a similar message" (BRSC1); another explained that although they "assess the situation from our own perspective … we always show the Hurricane Center's forecast; we don't deviate from that" (BRTX1).

4.1.1. Phase 1

During the first phase of their timeline, broadcast meteorologists described their primary decisions and actions as watching storms and forecasts to maintain awareness for themselves, their station, and their audiences, while communicating externally and internally in ways that "try not to get people too anxious" (BRGA1&2) because of the inherent uncertainty with storm development and track at this stage. Their information gathering and interpretation activities focus on tracking tropical disturbances, including current and potential TCs, and assessing their possible future evolution. This includes monitoring disturbances in the Atlantic Ocean throughout the hurricane season, even before a potential threat to their area is identified. It also involves paying close attention to trends (both over time and across information sources) in numerical weather prediction model output and available NWS products as well as comparing interpretations among meteorologists within the station and across information sources.

Broadcast Meteorologist Timeline: Illustrative quotes

Phase 1: Monitoring and Awareness

"We'll kind of put a feeler out if it's more than five days out. Say: Hey, it's possible that next week there could be a tropical something coming to the Gulf of Mexico. We're not too concerned about it right now, but we'll keep you informed. … We will use broad strokes to talk about it … and try to give some early guidance or general feel for which direction it may trend. Like right now we don't think it's going to be a threat to the Gulf, or we think this will come to the Gulf and it's too soon to say exactly where." (BRTX1)

Phase 2: Readiness & Action

"The closer that it gets to the event, it gets a bit wild at times because you're constantly updating, you're constantly on the air, you're trying to make sure you have the web stuff and your apps updated and fresh … it can get very, very busy." (BRSC1)

Phase 3: Transition to Impacts and Response

"When it gets 48 hours to impact, it's what's happening in the state, what's happening in our viewing area, how will it impact us?" (BRSC1)

"A lot of it, within 48 hours, is breaking it down by specific areas. The impacts, whether it's storm surge, wind or rain." (BRGA1&2)

Figure 4. Illustrative quotes for the three phases in broadcast meteorologists' decision and action timeline.

When engaging with the public during this phase, broadcast meteorologists said that they notify their audiences about potential TC threats, with the recommendation that people stay aware because the threats can and will change (Figure 4). They mention the TC on television and online, but typically do not yet increase on-air coverage by their weather team. In addition, several interviewees noted that during this phase, they may see or receive questions from members of the public based on what they believe to be misinformation posted on social media, e.g., overstatements of the risk that a TC poses to their region based on a model simulation that is highly unlikely or "has known biases in this range" (BRTX1). When this occurs, they "spend time batting down rumors" (BRTX1) to reassure people (Bica et al. 2020). They noted that this type of misinformation is more of an issue earlier in the timeline, when forecasts of storm track and evolution have greater uncertainty.

Internally, during this phase broadcast meteorologists may "start to meet as a station [and ask] what are the possibilities, what do you think is going to happen, what are the models trending, what are they saying, is there any cone of uncertainty yet?" (BRSC2). If a TC has the potential to affect their station's region, they may initiate discussions with station management, review station emergency plans, and "start to look ahead on a [staffing] schedule" (BRGA1&2).

4.1.2. Phase 2

The broadcast meteorologist interviewees described the second phase as a critical time period during which their TC-related activities ramp up significantly. Actions that began in the previous phase increase as the TC approaches, and if the TC poses a risk to their region, they transition from monitoring into getting ready and taking actions within their station.

As in the first phase, they continue to gather, compare, and interpret TC forecast information from the NWS and other sources, but with growing volume, specificity, and localization of information (Figure 2). They also discussed paying attention to NWS webinars and weather briefings as they come out and, in many cases, communicating with NWS forecasters, especially at their local WFO.

During this phase, broadcast meteorologists increase television coverage of the TC, e.g., through longer weather segments on the news and added cut-ins during programming. They also increase communication with the public on other media platforms, e.g., by sending out push notifications on apps, livestreaming on social media, and posting more updates to their station website and social media (Figure 4). In addition, as the available forecast information evolves during this phase, broadcast meteorologists shift to communicating more specific information. This includes using more localized reference points for explaining potential tracks and talking through more localized potential threats, such as regional and then county-by-county breakdowns of possible TC hazards and impacts. They described conveying forecast uncertainty by presenting viewers with possible storm scenarios, as well as explaining the "why" behind the forecasts and scenarios. They also relay preparation recommendations, evacuation updates, and other information from emergency managers, law enforcement, and elected officials through the communication mechanisms above as well as on-air live updates and news coverage of press conferences.

Internally, during this phase, broadcast meteorologists discussed having more meetings with management and their weather teams and "starting to get into the nitty gritty of [media] coverage plans" (BRSC1). This includes deciding about staffing schedules and reporter deployment, in coordination with partner stations if additional staff or resources are needed. As the storm gets closer, their station puts its hurricane plans into action to ensure that staff have safe shelter, food, and water during the storm, and they also take any actions needed to protect their own families.

4.1.3. Phase 3

This phase, as BRSC1 described, "is our Super Bowl." Broadcast meteorologists continue to gather and provide updated forecast and other official information as it is issued, including NWS watches and warnings, evacuation updates and preparation recommendations, and storm-related press conferences from local and state officials. As the storm nears and then begins to affect their area, they are also increasingly able to use observational data (including images from radar, reporters, and members of the public) to track and understand the storm's characteristics and impacts.

During this phase, broadcast meteorologists' communication and engagement with their audiences continues to increase through more frequent or even wall-to-wall (24-7) television coverage, as well as on-screen crawlers, app notifications, and website and social media updates. Their emphasis shifts to "giving people much more specific information, with more certainty on where landfall will occur, about the time that it will occur," (BRTX1) as well as forecasts of when hazards and impacts are expected in different areas within their viewer region (Figure 4). As the storm nears and then begins to affect their area, they also increasingly use observational data (including radar, live news coverage from reporters, and images from members of the public) to track the storm and its impacts and to show viewers what is happening and how it may affect them.

Within their organization, broadcast meteorologists increase the number of meteorologists on shift to manage their increased media coverage of the storm, and they finalize field reporter deployment. They may also increase coordination and communication with partner stations to receive or allocate additional staff or other needed resources. They continue to implement emergency plans and prioritize the safety of staff, including deciding when to pull reporters out of certain areas or move station staff to safety if needed.

4.2. Emergency Manager Decision and Action Timeline

Emergency managers discussed four intersecting types of activities that they engage in during TC threats: information gathering and interpretation; communication, coordination, and advisement within their agency, with elected officials, and with local, regional, state, and federal partners; communication with members of the public; and evacuation and resource staging. An overview of these activities in different phases of TC threats is provided in Figure 5, and illustrative quotes are provided in Figure 6.

Across the timeline, emergency managers' information-gathering and interpretation activities focused on maintaining awareness and obtaining up-to-date forecasts about the storm's track and potential hazards and impacts in their region. Although several interviewees noted that they may look at forecasts from other sources for situational awareness, they reported making most of their decisions using forecast information from the NWS rather than other sources. They interpret and use forecast information on its own, and sometimes integrate information into decision support tools such as HURREVAC/HVX[13]. Emergency managers use this information to communicate about the TC and coordinate evacuations, resource staging, and other preparedness activities across the governmental, non-profit, and private sector organizations that provide emergency support functions (ESFs),[14] such as transportation, public works, search and rescue, mass care, and health services. They also communicate with and advise agency leadership, elected officials, and others making decisions that influence public safety, such as educational institutions and

[13] HURREVAC, recently updated to HVX, is a decision support tool for government emergency managers developed and supported by the U.S. National Hurricane Program. It enables combining TC scenarios and NHC forecasts with emergency management decision timelines, e.g., for evacuation. Although many interviewees discussed using HURREVAC/HVX, two working in a smaller emergency management agency noted that they do not, because they lacked sufficient staff to allocate time for training on the system or for using it during TC threats.

[14] ESFs provide an organizational structure for grouping and coordinating the different types of resources, support, and services that are likely to be needed to prepare for, manage, respond to, and recover from disasters and other emergency incidents. There are 15 ESFs. See, e.g., FEMA (2021).

businesses. In addition, they may coordinate or participate in communication with the public about the risks and recommended actions, e.g., through press conferences, social media, and emergency notification systems. Although emergency managers' specific roles in evacuations and other decisions vary based on their level of governance, state, jurisdiction, and job characteristics, this set of activities was relevant across the emergency managers interviewed.

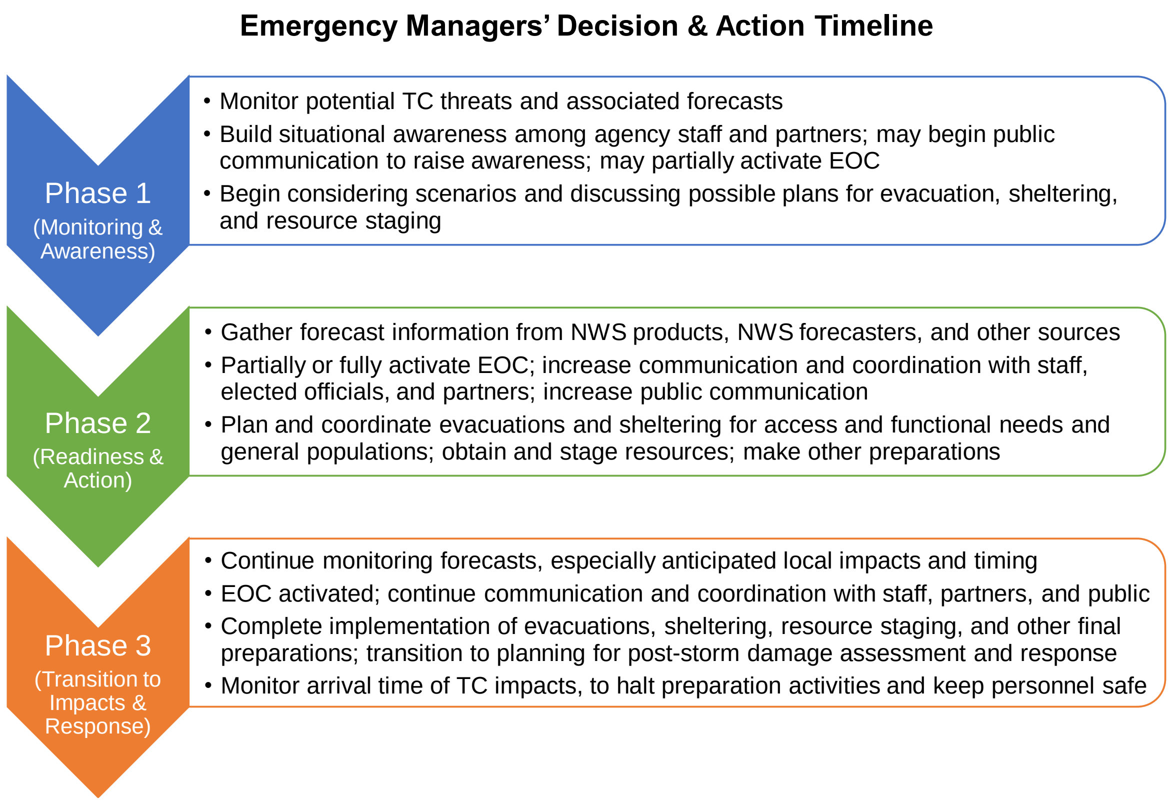

Figure 5. Overview of emergency managers' major decisions and actions during TC threats, for each of the three phases in the timeline depicted in Figure 2. Additional information about each of the activities shown is provided in section 4.2, and illustrative quotes for each phase are provided in Figure 6.

During TC threats, emergency managers described their goals as ensuring public safety and well-being. They aim to do so by maintaining sound situational awareness for themselves and others making decisions, coordinating decisions and actions across public safety functions, and clearly communicating with partners and the public about impending storm threats, public safety measures, and recommended protective actions. This includes a focus on planning and helping implement evacuation and sheltering of at-risk members of the public, if needed, and obtaining and positioning resources for pre-storm protective actions and post-storm response and recovery.

4.2.1. Phase 1

During the first phase, emergency managers described their primary activities as monitoring potential threats, building situational awareness, and, if a TC might threaten their region, beginning to consider scenarios and discuss possible plans. Some said that they begin daily monitoring of potential TCs in the Atlantic at the start of hurricane season; another described starting to look at forecasts "anytime a potential system pops up" (EMGA4). Similar to broadcast meteorologists, during this phase emergency managers discussed paying attention to weather prediction models as well as available NWS TC forecast products. Several also discussed being in contact with the NHC (e.g., through the FEMA Hurricane Liaison Team) or staff at their local WFO (e.g., the Warning Coordination Meteorologist) beginning in this time range.

If it appears that a TC might approach their region, emergency managers begin notifying their agency staff, leadership, and partners, to build their situational awareness, and begin discussing actions that may need to be taken later in the timeline (Figure 6). In particular, interviewees emphasized that effectively implementing pre-storm evacuations and post-storm response requires taking a number of earlier actions; thus, during this phase they may begin to consider options for decisions such as evacuation areas and routes, bussing and medical transport, sheltering, and staging resources. They may also begin to coordinate staffing for the event and partially activate their Emergency Operations Center (EOC) to support enhanced monitoring and initial logistical discussions. In addition, depending on the storm situation, they may start communicating with the public about the TC.

Emergency managers reported that they understand that this far in advance, much can change with TC-related forecasts. Therefore, they are paying attention to forecast information and considering future actions but typically not yet committing to major decisions or resource allocations (Figure 6).

4.2.1. Phase 2

Similar to broadcast meteorologists, emergency managers described the next phase as a critical time period, during which their roles transition from building situational awareness and considering plans to taking critical actions, e.g., making decisions about evacuations and acquiring and staging resources. As one emergency manager explained, it is at "120 hours that we have to start making real decisions that cost real money, that affect real people" (EMTX4&5). During this phase, emergency managers obtain forecast information from official NWS products as they are released, as well as through NWS decision support briefings, conference calls, and discussions. They are especially interested in information about the storm's potential hazards and impacts in their area of responsibility, including storm surge, strong winds, and flood-inducing rainfall. They also monitor television and social media to maintain awareness of what others are communicating and how the community is interpreting and responding to the threats. If impacts are anticipated in their region, emergency managers activate or ramp up their EOC and staffing during this phase, and they increase communication and coordination within their agency and with elected officials and partners so that everyone involved in making public safety decisions has "the best information available at the time to make whatever decision needs to be made" (EMSC2).

One major set of decisions that typically needs to be made during this phase relates to public evacuations. The timing of evacuation order decisions may appear straightforward, working backwards from the anticipated arrival of TC impacts using an area's clearance time. However, interviewees emphasized that hurricane evacuations are complex processes that involve multiple intersecting considerations and decisions that must be made prior to a voluntary or mandatory evacuation announcement. One such complexity is the different timelines involved in successfully evacuating the general population versus access and functional needs populations, in other words, people who may need assistance evacuating. For the general population, emergency managers plan to initiate evacuations with sufficient time for people to finish moving to safety prior to arrival of impacts, which involves considering clearance times. Safely moving access and functional needs populations, including those with disabilities, who are at hospitals or long-term care facilities, or who lack transportation or other means to evacuate, requires additional time and resources. Thus, evacuations for these populations are often initiated prior to calling a general evacuation, as early as 72 hours prior to anticipated arrival of TC impacts.

Emergency Manager Timeline: Illustrative quotes

Phase 1: Monitoring and Awareness

"If it's quite a distance away out in the Atlantic, I usually wait until it becomes a tropical depression or tropical storm to send out emails to all our partners … and make everyone aware. … That's really to get everybody primed for okay, we may see something. Try to give an idea of: especially this timeframe, keep an eye on it." (EMSC2)

"A lot of awareness, lot of looking forward to the next four to five days." (EMGA1)

Phase 2: Readiness & Action

"Once we get inside 96 hours … we have probably 300 items that we have to take care of. Those items are starting to be clicked off. We've ordered buses. We're doing evacuations. We've ordered commodities … Hospitals are being evacuated. All these things are all starting to take place based on the impacts. If we're expecting surge … we might not have issued [an evacuation order] at 120 hours, but we're at least talking to the public about it, that we might have to do these evacuations. So, we're working to soften the public up for this message to come in, probably tomorrow at this time, we'll probably be issuing a mandatory for such and such. All those things have to take place." (EMTX4&5)

"In order to call up all of the resources that the local jurisdictions will need to help them and evacuate a populace, we have to have the time to identify those resources and where they are, mobilize them … The decision to evacuate becomes a very difficult decision because that takes time, but it also takes a lot of money. We're talking about multimillion dollar [transportation] contracts that have to be activated … and you're asking [industry and the port] to shut down … So there's going to be a tremendous economic loss to call an evacuation. Also, you're looking at the human factor. If you call for an evacuation, you're going to ask nursing homes, assisted living facilities, that may have patients that are medically critical, that may have to evacuate. So they have to weigh that risk against the potential that the storm is going to make a landfall here and it will be devastating." (EMTX1)

Phase 3: Transition to Impacts and Response

"It's over at 48 [hours]. Things have to be completed or rapidly coming to closure as far as timing on all the lists and things that we have to do." (EMTX4&5)

"If we're 12 hours away from [onset of tropical storm force winds] and there's something we haven't done, then we've got a problem. … We call this phase OPCON 1. We call it final staging … within 24 hours … it's more like details at that point." (EMGA3)

Figure 6. Illustrative quotes for the three phases in emergency managers' decision and action timeline.

Moreover, successfully implementing evacuations requires emergency management organizations and their partners to plan logistics and expend significant resources earlier in their timeline. Time, personnel, equipment, and funds are needed to notify affected populations, manage traffic, identify public shelter locations and set up shelters, arrange bussing and medical transportation, and so on. These actions must be coordinated across multiple public, non-profit, and private sector organizations, often starting 96 or 120 hours before arrival of TC impacts (Figure 6). Thus, forecast information during this phase is critical for setting up successful public safety decisions and actions as the storm approaches.

Interviewees described how decisions about who to evacuate, where, and when and who is safe to stay in place are based on the forecasted storm hazards and the anticipated extent of different types of impacts. Different populations can face different risks; for example, people in coastal evacuation zones are typically evacuated due to risk of inundation from storm surge, while hospitals and long-term care facilities may also be evacuated due to the risk of strong winds and associated power outages. Mobile home residents are also more susceptible to TC winds, even inland. Given these different risks and potential evacuation traffic, evacuations can be sequenced, for example, by starting with a voluntary evacuation order or evacuation of people at highest risk, and then transitioning to a mandatory or larger-scale evacuation order if conditions warrant as the storm gets closer and forecast uncertainty decreases.

Along with evacuations, emergency managers described many other preparation activities that must be coordinated during this phase (Figure 6). Examples include issuing emergency declarations; closing schools and other facilities; allocating and positioning additional resources that may be needed for preparedness and post-storm response (such as sandbags, rescue equipment, fuel for generators, food, and water); and requesting additional resources from other jurisdictions if they may be needed.

Another critical activity during this phase is public communication, which includes disseminating accurate, updated information about the threats and recommended actions to as many people as possible. Interviewees described ramping up public communication via multiple mechanisms, described above. As EMTX4&5 explained: "Communication, communication, communication. Every three to six hours, you have to be in front of the public telling them what the status is."

Emergency managers noted that although forecasts are uncertain during this phase, they still have major, expensive decisions to make that are difficult or impossible to implement effectively beyond a certain point. One way that they manage this uncertainty is to consider scenarios for their area, for example, a storm that makes landfall a category higher than predicted or shifts track and generates greater impacts, and then monitor trends in the forecast. Nevertheless, it is often challenging to make costly, critical decisions given the uncertainty in TC forecasts and local impacts several days or more in advance, when decisions need to be made (Figure 6).

4.2.2. Phase 3

Within 48 hours prior to TC impacts, emergency managers shared that they have shifted to final readiness and staging (Figure 6). Depending on the region and the scale of the evacuation required, evacuations have already been determined and are being implemented, or final evacuation decisions are made during the beginning of this phase. In high-risk areas, emergency managers are continuing to facilitate evacuation or safe local sheltering for those who have not yet left or are unable to leave on their own. Inland and outside the highest-risk areas, they are managing traffic from evacuees traveling through and helping those who need gas or supplies or do not know where to take shelter. They also make other final preparations, such as having staff take any necessary actions for their own families, planning for continuity of government, shutting down transportation and other public services, and issuing curfews to clear roads.

Emergency managers continue to gather forecast and storm information during this phase. However, they said that by this time, forecasters are typically confident about whether a storm is coming their way and is likely to affect their area. Thus, they tend to shift their focus from larger-scale forecast features such as the storm's track to more detailed information such as anticipated local winds, storm surge, and rainfall and timing of their arrival (in conjunction with the tide, in coastal areas). Although major pre-storm decisions and expenditures have usually already been made, during this phase emergency managers continue to access forecast information. They use this information to make final decisions such as where to safely open shelters of last resort, position supplies and post-storm response crews, and house their critical workforce during the storm. They also monitor forecasts for any major changes in intensity or other factors that may affect plans in progress. As the storm approaches, they continue to monitor updated forecasts of arrival time of tropical storm force winds and other hazards, as well as storm observations, so that they can ensure that preparations are completed and that staff and first responders are in safe locations by the time hazardous conditions begin. In addition, they begin to keep an eye on when hazardous conditions are expected to end, to anticipate when they can initiate post-storm damage assessment and response activities.

During this phase, emergency managers continue to communicate frequently with the NWS and other decision makers and partners; they will have fully activated the EOC no later than 24 hours prior to impacts, to be ready to respond during and after the storm. They also continue communicating with the public, including notifying those who have not left about shelters of last resort and that emergency services will be temporarily suspended once hazardous conditions arrive. As the storm nears, they shift from pre-storm preparations to planning for during-storm operations and post-storm response. This includes monitoring when hazardous conditions are expected to end, using forecasts and observations, to anticipate when they can initiate post-storm damage assessment and response.

5. FORECAST INFORMATION USE

Building on the decision and action timelines above, next we examine what NWS TC products and other forecast information these NWS partners use in different phases of TC threats (research question 2). This includes synthesizing from the discussion in section 4 and the interview data which types of information they use from different sources, how they use that information, and what they find most useful for making decisions. Mirroring section 4, we present findings first for broadcast meteorologists and then for emergency managers, summarized in Figure 7 and 8, respectively.[15]

5.1. Broadcast Meteorologist Information Use

As discussed in section 4.1, most of broadcast meteorologists' TC-related activities focus around providing clear, accurate, and up-to-date media coverage (via television, social media, and other media platforms) of evolving TC threats to their audiences. Their use of different types of TC information as a storm evolves is therefore determined in large part by the availability of different types of TC information. Thus, much of their information use timeline (Figure 7) follows the progression of when, during the lifetime of a storm, different NWS TC products and other information are generated (Figures 1–2).

During the first phase, which is typically more than 5 days before TC impacts or before a TC has officially formed, the primary visual TC product generated by the NWS is the NHC Graphical Tropical Weather Outlook (Figures 1–2). All of the broadcast meteorologists interviewed shared that they use this product for monitoring, tracking, and communicating the locations of current and potential future TCs during this phase. One interviewee described it as "a true game changer" (BRTX1); another said that "this is the one that we're all living and dying by" during this phase (BRTX2). Because the NWS provides official TC track and intensity forecasts only out to five days, for information about possible TC tracks and other characteristics during this phase, broadcast meteorologists rely primarily on numerical weather prediction model output. Models mentioned include the GFS (U.S.), Canadian, and European global models as well as "spaghetti plots" depicting multiple possible TC tracks. As discussed in section 4.1, during this phase they use model information to assess threats, pick up on trends, and convey forecasts and their uncertainties.

During the second phase, as forecast skill increases, NHC and other NWS entities begin providing a number of additional forecast products that broadcast meteorologists use. This includes the NHC Track Forecast Cone, which provides forecasts of storm track and associated uncertainty out to five days, along with other information. Despite issues with people's interpretations and uses of the Track Forecast Cone, it is one of the most widely known NWS TC products (e.g., Broad et al. 2007; Bostrom et al. 2016, 2018), and all of the broadcast meteorologists referenced using it. As BRSC2 explained, once the Cone product becomes available, it provides "a one-stop shop that gives our viewers and our consumers a chance to get

[15] This section and Figure 7 and 8 are designed to examine broad patterns of information use across the interview data. Note also that information not listed in a given time frame may still be used by some broadcast meteorologists or emergency managers, but it was not a prominent theme in the interviews.

[key] information on one graphic," including a TC's position, current wind field, and forecasted track and intensity. Interviewees noted, however, that it is also important to understand and communicate the potential for impacts outside the cone.

Broadcast Meteorologist Timeline: Major Types of TC Information Used

Phase 1: Monitoring & Awareness	Phase 2: Readiness & Action	Phase 3: Transition to Impacts & Response
NWS TC Products		
▪ NHC Graphical Tropical Weather Outlook ▪ Forecast Discussions	▪ NHC Track Forecast Cone ▪ TC hazard forecasts: NHC TC Wind Speed Probabilities; NHC Arrival of Tropical-Storm-Force Winds; WPC and SPC products ▪ NHC Key Messages ▪ NHC Public or Forecast Advisories ▪ Forecast Discussions	Same NWS TC products as Phase 2 and ▪ Watches and Warnings: Hurricane / Tropical Storm; Storm Surge ▪ TC hazard forecasts: NHC Potential Storm Surge Flooding; WFO Hurricane Threats and Impacts graphics ▪ WFO Hurricane Local Statement
Other Information from NWS		
▪ Interpretations and updates from NWS forecasters, e.g., through webinars / conference calls, NWSChat	▪ Interpretations and updates from NWS forecasters, e.g., through webinars / conference calls, NWSChat	▪ Interpretations and updates from NWS forecasters, e.g., through webinars / conference calls, NWSChat
Modeling and Analysis Tools		
▪ Weather prediction models: global; spaghetti plots ▪ Vendor data analysis and display system	▪ Weather prediction models: global; spaghetti plots ▪ Vendor data analysis and display system	▪ Weather prediction models: global; regional; in-house; spaghetti plots ▪ Vendor data analysis and display system
Other		
▪ Observational data: satellite ▪ Weather information from private companies, web sites, social media	▪ Observational data: satellite; Hurricane Hunter aircraft; buoys ▪ Weather information from private companies, web sites, social media ▪ Information from public officials, e.g., preparedness, evacuation, closures	▪ Observational data: satellite; radar; Hurricane Hunter aircraft; buoys; river and tide gauges; reporter and public reports, pictures, and videos ▪ Weather information from private companies, web sites, social media ▪ Information from public officials, e.g., preparedness, evacuation, closures

Figure 7. Overview of the major types of TC information used by broadcast meteorologists during each of the three phases in the TC threat timeline depicted in Figure 2.

As a TC approaches, broadcast meteorologists discussed using multiple types of additional information to understand and convey more specific forecasts of TC hazards and impacts as well as evacuation and preparedness news and recommendations. In the second and third phases, this included NHC wind graphics, as well as WPC and SPC products if the TC may generate heavy rainfall, inland flooding, and/or tornadoes in their region. In addition, interviewees discussed using additional WFO products and NHC storm surge and watch/warning products as those become available, typically during the third phase. As their timeline progresses, they also described using more observational data (section 4.1), and a few discussed transitioning from using global to regional weather prediction model output.

Throughout their timeline, broadcast meteorologists noted the importance of their vendor-provided data analysis and display systems provided by private sector vendors for using and communicating TC products and information (section 4.1). They occasionally mentioned disseminating forecast information using NWS graphics and products directly, in the NWS format, e.g., when they were away from their office or for information not available in their software. More frequently, they use the data underlying the NWS products, ingested into computer software, to manipulate and combine data and create their own graphical products, often in a station-specific format. Several interviewees also discussed how they communicate TC products and information with the public across different media platforms. For example, for products and information that require additional explanation to be understandable to the public, they may focus on dissemination via television broadcasts or video posts where the broadcaster can provide a verbal interpretation, rather than disseminating as an image or text on social media.

Although some broadcast meteorologists said that they rely primarily on their own knowledge and discussions within their station's weather team for interpreting the forecast situation, many also discussed accessing information from NWS forecasters, to obtain interpretations, explanations, and insights beyond what is typically available in other NWS products. Most commonly mentioned were reading the Forecast Discussion products generated by different NWS entities and using NWSChat to interact online with WFO forecasters. Other mechanisms for obtaining knowledge and updates from NWS forecasters included WFO briefing packages, webinars, and conference calls and one-on-one interactions through telephone calls. Interviewees also noted the value of being able to obtain quickly understandable information about key forecast highlights through NWS products such as NHC Key Messages graphics, NHC Advisories, and, as a storm approaches, the Hurricane Local Statement generated by local WFOs. This is especially important when there are major forecast updates, so that broadcast meteorologists can process and clearly convey the updated information to their audiences as rapidly as possible.

5.2. Emergency Manager Information Use

As discussed in section 4.2, emergency managers' primary focus is on protecting public safety and well-being. Their information use timeline (Figure 8) is therefore driven by both when different types of information are available and how far in advance different public safety decisions, such as taking the multiple steps needed to successfully implement evacuations for general and access and functional needs populations, must be made. Although many emergency manager interviewees described accessing information from multiple sources, they emphasized that they rely primarily on forecasts from official NWS sources to make decisions. However, if decisions must be made before desired official forecast information is received, they will seek out additional information, if possible, and then make the decision using the forecast information available, along with experiential and other forms of knowledge.

In the first phase of TC threats, emergency managers discussed accessing forecast information from the NHC Graphical Tropical Weather Outlook and weather prediction model output, especially in the form of spaghetti plots. As discussed in section 4.2, they use this information to monitor potential threats, build situational awareness, and, depending on the likelihood of a TC entering their region, begin considering possible plans for different scenarios.

Beginning in the second phase, as multiple NWS entities start to issue more types of TC products, emergency managers discussed using many of the same types of information as broadcast meteorologists to assess, communicate, and prepare for different aspects of TC risks. Similar to broadcast meteorologists, emergency managers described the NHC Track Forecast Cone as providing a useful high-level overview of a TC's potential track, timing, and intensity, although again some discussed challenges with people misunderstanding it (including the potential for TC impacts outside the cone). In addition, during the second phase, many emergency managers described using spaghetti plots from non-NWS sources to assess possible TC tracks and situation-specific track uncertainties.

Emergency Manager Timeline: Major Types of TC Information Used

Phase 1: Monitoring & Awareness	Phase 2: Readiness & Action	Phase 3: Transition to Impacts & Response
NWS TC Products		
▪ NHC Graphical Tropical Weather Outlook ▪ Forecast Discussions	▪ NHC Track Forecast Cone ▪ TC hazard forecasts: NHC TC Wind Speed Probabilities; NHC Arrival of Tropical-Storm-Force Winds; WPC and SPC products ▪ NHC Key Messages ▪ NHC Public or Forecast Advisories ▪ Forecast Discussions	Same NWS TC products as Phase 2 and ▪ Watches and Warnings: Hurricane / Tropical Storm; Storm Surge ▪ TC hazard forecasts: NHC Potential Storm Surge Flooding; RFC products ▪ WFO Hurricane Local Statement
Other Information from NWS		
▪ Interpretations and decision support from NWS forecasters, e.g., through webinars / conference calls, one-on-one conversations, other interactions	▪ Interpretations and decision support from NWS forecasters, e.g., through webinars / conference calls, one-on-one conversations, other interactions	▪ Interpretations and decision support from NWS forecasters, e.g., through webinars / conference calls, one-on-one conversations, other interactions
Modeling and Analysis Tools		
▪ Weather prediction models and spaghetti plots ▪ HURREVAC/HVX	▪ Weather prediction models and spaghetti plots ▪ HURREVAC/HVX	▪ HURREVAC/HVX
Other		
▪ Observational data: satellite ▪ Weather information from television, web sites, social media	▪ Observational data: satellite; buoys ▪ Weather information from television, web sites, social media	▪ Observational data: buoys; river and tide gauges; radar ▪ Weather information from television, web sites, social media

Figure 8. Overview of the major types of TC information used by emergency managers during each of the three phases in the TC threat timeline depicted in Figure 2.

For information about potential TC hazards and impacts during the second and third phases, many interviewees discussed using NHC Wind Speed Probabilities and Arrival of Tropical-Storm-Force Winds graphics. Depending on the situation, they also noted using products from WPC, SPC, River Forecast Centers (RFCs), and their local WFOs. In addition, emergency managers in coastal areas discussed the importance of storm surge risk information, as well as the intersection between the timing of TC-induced flooding and tides. Several described coastal flood forecasts as especially important during the second phase, when critical and expensive decisions leading up to evacuations often need to be made, even though this is before the NWS currently issues storm-specific storm surge inundation products.

One major group of NWS products provided during the third phase is tropical storm, hurricane, and storm surge watches and warnings; these are not issued until 48 and 36 hours prior to anticipated impacts, respectively. Given the evacuation decision timelines discussed in section 4.2, several emergency managers explained that they do not use these products to inform decisions about evacuation orders. Rather, they typically use watches and warnings as justification for evacuation orders that have already been decided on, or to provide an additional inducement for people to evacuate or make other preparations. This does not mean, however, that watches, warnings, and forecasts provided within 48 hours of impacts are not useful; evacuations are being implemented, and emergency managers, businesses, members of the public, and others can and do still make protective decisions in the hours leading up to a storm's arrival. As the storm nears and arrives, emergency managers continue to use forecasts and observational information to make final pre-storm preparations, decide when to halt all preparations and emergency services, and then decide when and how to initiate post-storm response.

Throughout their timeline, emergency managers discussed using TC forecast information on its own as well as potentially in HURREVAC/HVX or GIS to enable overlaying the forecasted TC hazards with other geospatial data, such as the locations of evacuation zones or critical infrastructure in their jurisdiction. Similar to broadcast meteorologists, they also discussed the value of quickly understandable forecast highlights provided in products such as the NHC Key Messages graphic. However, some explained that due to NHC's national and international focus, the Key Messages product typically provides coarser-scale information that emergency managers must narrow down to their jurisdiction. In addition, a few noted that the national or multistate geographic scale of most NWS graphical TC products can make it difficult to extract locally relevant information that they need. Thus, many emergency managers shared that they look to their local WFOs for information about the "particulars about our area and how it's going to impact us" (EMTX1) that they can use in making the decisions discussed in section 4.2. They obtain this information through WFO-generated graphics and briefing packages as well as directly from WFO forecasters through webinars, conference calls, conversations, and other interactions. A few interviewees also discussed accessing forecasters' interpretations through Forecast Discussion products or the FEMA Hurricane Liaison Team located at NHC. Summarizing the value to emergency managers of information and decision support services from NWS forecasters, in conjunction with NWS TC products, EMTX2&3 said: "I don't see how you could do this job and not be on pretty close terms with your [local] weather service."

6. KEY INFORMATION GAPS AND RECOMMENDATIONS

Generally, broadcast meteorologists and emergency managers said that they find NWS information and products very useful. However, they also discussed unmet information needs and recommended areas for improvement in the NWS TC product suite. In this section, we synthesize their comments, in conjunction with the analysis in sections 4 and 5, to identify key information gaps and propose associated recommendations (research question 3). Illustrative quotes are provided in Figures 9 and 10.

As described above, our project included collaboration with a core team of NOAA Research and NWS personnel, who helped us interpret our research findings in the context of NOAA policies, practices, and planning, and they provided feedback as we began formulating and then refined recommendations. This enabled us to coproduce research-guided recommendations that are usable by NOAA in a variety of ways. For example, although some aspects of the recommendations can be implemented by NHC or WFO forecasters as part of their current products and services, many were designed to help NOAA prioritize modernizations to the TC product suite and support longer-term NOAA Research and NWS planning.

One theme that emerged across our data was the *timing of NWS product releases*. For broadcast meteorologists, the primary issue noted was the timing of major NWS TC product releases relative to the timing of television newscasts, accounting for the time they need to prepare for going on air. Although broadcasters can ad-lib on television when necessary, a few minutes to digest forecast updates and prepare new visuals can help them more effectively convey the latest information from NWS to the public (Figure 9). This issue has been identified in prior work (e.g., Demuth et al. 2012), but it is difficult to solve, because NWS forecasters must themselves wait for the latest observations and model output and engage in their own activities in order to generate TC product packages. Nevertheless, considering new ways to address this issue can help broadcast meteorologists fulfill their role as partners with the NWS in communicating with members of the public. Thus, **we recommend that NOAA collaborate with broadcast meteorologists to develop strategies for informing them about key TC forecast and warning updates prior to standard television broadcast times — especially when there are delays in releasing the full product package**. Based on our interviews, key updates are those that may affect major television visuals or communication approaches; examples include upgrading or downgrading a storm between a tropical storm and hurricane, significant changes in track or intensity forecasts, and issuance of new watches or warnings. Possible strategies to consider further include early release of selected products or data within the existing TC package, when needed; an additional (potentially embargoed) product informing broadcasters of updates in progress; or a national-level NWS broadcaster liaison position to coordinate providing this information and other decision support for broadcasters.

For emergency managers, the primary timing issue was when, leading up to TC impacts, certain types of NWS forecast information were unavailable when decisions needed to be made. This information gap was most prominent during the second phase, when actions must be taken to enable successful evacuations of both general and access and functional needs populations. Coastal emergency managers, in particular, discussed the importance of TC-specific storm surge forecast information at greater than 48 hours of lead time, even though they are aware of the uncertainties and challenges in providing that information. Thus, **we recommend that NOAA**

improve communication of TC-specific storm surge risk at greater than 48 hours of lead time. As part of addressing this issue, NHC provides storm surge hazard maps for use in longer-lead-time planning and operations (Zachry et al. 2015). NOAA and the research community are also working on reducing uncertainty in storm surge forecasts and extending TC-specific surge forecasting capabilities earlier, to enable providing such information. (NOAA 2019). However, the inherent uncertainties in location-specific storm surge predictions (Fossell et al. 2017) and the feedback provided by our interviewees suggest that additional strategies are needed. Consequently, in addition to ongoing efforts, **we recommend that NOAA and the research community develop alternative product formats for conveying storm surge risks at greater than 48 hours of lead time, with an emphasis on providing the best possible information for supporting the public safety decisions made in this time frame**.

Information gaps and recommendations: Illustrative quotes #1

Timing of NWS product issuance and availability

"During a tropical situation, you're sitting there on pins and needles because an [NWS] update's supposed to come out at 02:00, 05:00, 08:00, 11:00 and sometimes they get it out 15 minutes ahead, sometimes it's 2 minutes behind. And the problem is we're on the air at 11:00 PM, and, of course, they're going to want weather first.... And then we'd have to build the graphics … It will update on its own to a degree, but you still have to tweak it, which even if it only takes 45 seconds, that's 45 seconds. And it's critical in TV broadcasting." (BRGA3)

"We would need to begin a vulnerable population evacuation no later than about 72 hours from landfall, which is a long time. But in order for us to start that evacuation three days out, we have to activate contracts and sign contracts with bus companies, ambulance companies, different things like that either four or five days from landfall. So … we have some pretty big questions with a lot of money attached to it that we have to start asking ourselves about five days out. Because if we wait until three days out or, you know, two and a half days out to start that vulnerable population evacuation, it's going to bleed over into the general population evacuation. And it's going to create kind of a chaotic situation." (EMGA3)

Product understandability and usability

"These two next pages [NWS products], I'll be honest with you … I find myself having a difficult time understanding it myself, much less trying to explain it to our viewers." (BRSC2)

"We take what the National Weather Service puts out and, I'll say, craft it. We put it in a format we can use and get it to our folks in a fairly understandable manner." (EMGA5)

Figure 9. Illustrative quotes for key information gaps and recommendations, part 1.

A second theme was the *understandability and usability of NWS TC products*. Members of both groups talked about the difficulties that they and others have in effectively interpreting and using certain NWS products (Figure 9). Broadcast meteorologists, in particular, reported that whenever possible, they use the data layers underlying NWS products to create modified graphics that are more intuitive and visually appealing, with more accessible language. It is therefore easiest for them to broadly, effectively disseminate TC information when the data layer is available and straightforward to process in their software. Moreover, the popularity and widespread usage of the NHC Track Forecast Cone, despite issues with its interpretation, demonstrates the challenges of changing a product's format once it is familiar, and thus the value of incorporating a range of user perspectives into a product's design early in its formulation. Thus, **we recommend that**

NOAA and the research community continue to invest in designing more readily usable product formats and data layers, by integrating users' perspectives into research and development beginning early in a product's formulation and evaluating products with users prior to release. In doing so, it is important to recognize that NWS products have several major pathways for use: in their original format, as a starting point for revision prior to further dissemination, and as data layers that can be used to create new visuals or be integrated with other data to generate new information.

Many of the decisions that emergency managers and others make during TC threats depend on the anticipated TC hazards and impacts in their area, and sometimes at specific location. Thus, a third theme from our analysis was *interest in locally relevant forecast information whenever possible* (Figure 10). In some situations, the primary need expressed by emergency managers was being able to zoom in or otherwise obtain local (e.g., county-level) information from larger-scale graphical products; therefore, **we recommend that NOAA explore options for interactive product formats and delivery, working closely with forecasters and key partners throughout the development cycle to ensure appropriate content and design**. In other situations, emergency managers are seeking more localized information than current TC forecast products provide. To help address this, research is ongoing to improve TC forecast skill, including geographically specific predictions of TC hazards and impacts. However, given the unavoidable uncertainties in TC forecasts, complementary efforts are needed. Thus, **we recommend research and development to co-design and co-evaluate new ways of communicating forecasts of TC hazards that are usable in local decisions, at lead times when geographically specific forecast information is highly uncertain**. Such products might convey regional risks, or, given interviewees' discussions of using scenarios for communication and decision making, they might take a scenario-based approach.

Another key theme was the *importance of concise, easily understandable highlights that help people quickly extract key information from the NWS TC product suite* (Figure 10). In particular, interviewees noted the value of high-level takeaways such as those in the NHC Key Messages graphic, for themselves and for members of the public. Several suggested using easily accessible, synthesized key points on other TC products. Similar key points can also be found in other NWS products, such as NHC Advisories and WFO Hurricane Local Statements; however, interviewees said that these textual products provide a lot of information to sift through, can be difficult to find, and may not be available at the lead times when key decisions need to be made. Moreover, interviewees said that the key points currently provided by NWS are sometimes wordy, and some emergency managers noted that, consistent with NHC's role, NHC's Key Messages are often not specific or localized enough to be useful for their decisions. Therefore, **we recommend that NWS expand the use of "plain language" highlights to additional graphical products**. Individual WFOs are best suited to provide specific, local information, and although some WFOs do provide locally relevant graphical summaries with text highlights, they are not always easily accessible or widely disseminated. Thus, we also **recommend extending the "key messages" concept to all TC-affected WFOs so that, collectively, NWS is providing all potentially affected regions with readily accessible, locally relevant messaging beginning several days or more in advance of impacts**. Being able to quickly find and understand up-to-date information from the NWS through these types of products is especially important when risks are changing quickly, such as when a forecast track shifts or a TC rapidly intensifies.

Information gaps and recommendations: Illustrative quotes #2

Locally relevant forecast information

"We'll usually start off with the broad view showing the current storm's location, the expected path it is projected to take … And then, we would zoom down to our local region and populate on a few of our well-known cities the probability of receiving the hurricane force winds or the tropical storm force winds, or the general range of rainfall." (BRTX1)

"Not zoomed this far out. We'll want one much more local from the Weather Service…. zoomed in where we can see our county or at least our region." (EMTX2&3)

Concise, easily understandable highlights to help extract key information

"If there's any way to have more of those quick bullet points, I think those really help out a lot." (BRSC1)

"We'll work to see what are those key things that the products are indicating that are critical, whether it be wind, rainfall, flooding, tornado chance, whatever those things are. And then we make sure that we're really highlighting that stuff out to our partners, as well as within our own graphics that we're creating to message to the public." (EMGA4)

Value of human forecasters

"Our forecast office here in [location] is amazing. They have constant conference calls. They have webinars. … they are constantly feeding us one-sheeters leading up to a potential threat" (BRSC2)

"If there's things that I'm not clearly understanding, then that's when I reach out to [names of people at local WFO], and they always put it in terms that I can understand and what it means for us here locally." (EMTX1)

Figure 10. Illustrative quotes for key information gaps and recommendations, part 2.

A final theme that emerged was *the value to NWS partners of human forecasters' interpretations and decision support* (Figure 10). Broadcast meteorologists discussed obtaining from NWS forecasters the most up-to-date forecast information and interpretations. Emergency managers emphasized the value not only of hearing NWS forecasters' updates and interpretations, but also of having conversations with forecasters for decision support. This indicates that while timely, clear, and applicable TC forecast products and data are undoubtedly critical for NWS partners, the human dimension accompanying products and data is also critical (Figure 10). Consequently, **we recommend that efforts to modernize the TC product suite continue to support and emphasize the contributions of NWS forecasters' expertise and interactions with partners along with providing improved data**. This means recognizing and valuing forecasters' ability to distill complex, uncertain data into situationally relevant, readily interpretable information, which they can communicate (a) via plain language highlights and the key messages concept, as suggested in the above recommendations, and (b) directly with partners per their decision support needs. This also means more fully realizing the potential of human relationships and trust to act as "force multipliers" in effective NWS decision support and product creation (Uccellini and Ten Hoeve 2019). Actualizing these recommendations will involve ensuring that forecasters have the time, training, support, and other resources needed to engage in such activities, as well as regularly incorporating the perspectives of forecasters into product and service development and testing. It may also involve thinking more intentionally about NWS partnerships, in ways that evolve one-way or back-and-forth communication of information into strategic collaborations aimed at achieving common goals.

The interviews suggested several other potential information gaps, including additional information about TC hazard timing (see also Demuth et al. 2020); TC track forecasts more than five days in advance, potentially in a form similar to the spaghetti plots already used by many of the interviewees; and compiled information about TC threats in one product or place. These, along with other aspects of our findings, were subsequently investigated further through a survey with a larger sample of broadcast meteorologists and emergency managers (Bostrom et al. 2022).

7. CONCLUSION

This study aimed to contribute new understandings about key NWS partners' information needs for decision making during TC threats and to propose priority areas for modernizing the NWS TC product suite. To do so, we used insights from in-depth interviews with broadcast meteorologists and emergency managers, interpreted in the context of other literature, to investigate the types of decisions these NWS partners make, the actions they take, and the information they use during different phases of TC threats. We then analyzed key information gaps and potential opportunities for improvement in the NWS TC product suite and, more broadly, TC risk communication. Along with improving TC forecast communication in the near term, this work can strengthen the foundation for longer-term improvements by helping NOAA and the meteorological community prioritize investments in TC forecasting research and research-to-operations transitions.

TC forecasts and their communication have changed significantly in recent years, and they will continue to evolve. Thus, it is important for NOAA to find ways to be agile and adaptive, while also continuing to provide products and services that support the agency's mission. Doing so may involve not only modernizing existing TC products and filling gaps in the current TC suite, but also rethinking larger aspects of NWS strategy. For example, given today's rapid, multi-actor communication of weather information across multiple channels, would it be beneficial for NWS to modify its current approach to releasing regularly scheduled TC product packages? Given the growing volume and complexity of TC forecast and warning information, how can NOAA integrate the provision of products, data, and human forecaster interpretations and decision support to best serve its audiences' different needs? Navigating these types of questions is interlinked with NWS's ongoing evolution toward a next-generation forecast and warning framework and impact-based decision support services (Rothfusz et al. 2018, Uccellini and Ten Hoeve 2019). More broadly, we recommend that NOAA approach improvements to TC products as part of a broader risk communication strategy that involves effectively partnering with broadcast meteorologists, emergency managers, and others to communicate the latest TC forecast and warning information widely and translate this information into public safety decisions.

The results presented synthesize themes that emerged across interviewees. However, for some topics (such as preferences for specific products and interest in forecasts of storm surge versus other TC hazards), NWS partners' perspectives varied based on geography, resources, experience, and other factors associated with their decision-making contexts. Thus, additional exploration is needed of emergency managers' and broadcast meteorologists' decision timelines, TC information use, and unmet TC information needs across a wider range of jurisdictions and media markets. To extend our understanding in these ways and enhance the generalizability of these findings and recommendations, we followed these interviews with online surveys of broadcast meteorologists and emergency managers throughout TC-affected regions of the contiguous United States (Bostrom et al. 2022). We then synthesized results across the interviews and surveys to develop a compiled set of highlighted findings and recommendations (Morss et al. 2022b). Through this multi-method investigation, we aim to improve how NOAA, broadcast meteorologists, emergency managers, and others work together to benefit the U.S. public when TCs threaten.

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APPENDIX 1. INTERVIEW GUIDE

I. INTRODUCTORY QUESTIONS

1. Could you please briefly describe your position within your organization, including your core activities and responsibilities?

2. How long have you worked in this position? _______________

3. How many years of experience do you have in this type of work? _______________

4. When a tropical cyclone, or hurricane, threatens, what are your major job roles?

II. DECISION TIMELINE AND INFORMATION USE

Now we are going to talk about what your organization does during a tropical cyclone threat, which is a potential incident/event that *may or may not* happen, or an actual incident/event that affects your area.

For the purpose of today's interview, we are defining a tropical cyclone threat as: *a range of situations from a tropical depression or tropical storm to a category five hurricane, along with the hazards associated with these threats (such as: extreme winds, storm surge, heavy rainfall, and inland flooding, rough surf and rip currents, and/or tornadoes). This is meant to be an umbrella term that captures all incidents/events that could fall under a tropical cyclone threat.*

We are going to ask you to <u>walk us through the decisions you make or actions you take throughout a tropical cyclone threat, starting from</u> when you first become aware of a threat and continuing as the threat evolves until the end of the storm. For this discussion, we will break this out into three overarching time frames: 1) when you first become aware of a threat to about 5 days out from when a storm is expected to affect your area; 2) about 5 days to 48 hours out; and 3) 48 hours out until landfall or impacts. As we talk, feel free to adjust these time frames depending on what makes the most sense for you.

In doing this, we would like to understand what your different decisions or actions are and their timing. We would also like to learn about the tools/information you use to make these decisions/actions — including how the forecast information and products you use may evolve during a TC threat.

5. During the timeframe when you <u>**first become aware of a threat leading up to about 5 days before a storm is expected to affect your area**</u>, what decisions need to be made/actions need to be taken, and how are you involved in those decisions? [*If not already answered*] When do these decisions need to be made? [*For broadcast mets, we could ask: "During this timeframe, what do you show/say to your audience?"]*

    a. Are there any additional decisions you make / actions you take during this timeframe? And when do they need to be made? [*no matter how small the decision(s)*]

    b. What forecast information do you find most useful during this timeframe and what are you looking for?

c. From whom/what organizations do you obtain this information? How? (*Prompt for information from different NWS entities, e.g., NHC, local forecast office, other centers, and commercial services*)

d. Do you have suggestions for how this information could be improved to fit your decision-making needs? Is this information available when you need it? (*Prompt for kinds of forecast information they typically want to have and what they look for in the information (e.g., rates, amounts, update frequency, uncertainty information).*)

e. [*If not already answered*] Is there additional forecast information that you'd like to have during this timeframe? That would make your decisions easier/more effective/increase your confidence? (e.g., is there a way NWS/NHC could enhance your decision-making process?)

6. During the timeframe where **a threat is five days out to about 48 hours before a storm is expected to affect your area,** what decisions need to be made/actions need to be taken, and how are you involved in those decisions? [*If not already answered*] When do these decisions need to be made? [*For broadcast mets, we could ask: "During this timeframe, what do you show/say to your audience?"]*

   a. Are there any additional decisions you make / actions you take during this timeframe? And when do they need to be made? [*no matter how small the decision(s)*]

   b. What forecast information do you find most useful during this timeframe and what are you looking for?

   c. From whom/what organizations do you obtain this information? How? (*Prompt for information from different NWS entities, e.g., NHC, local forecast office, other centers, and commercial services*)

   d. Do you have suggestions for how this information could be improved to fit your decision-making needs? Is this information available when you need it? (*Prompt for kinds of forecast information they typically want to have and what they look for in the information (e.g., rates, amounts, update frequency, uncertainty information).*)

   e. [*If not already answered*] Is there additional forecast information that you'd like to have during this timeframe? That would make your decisions easier/more effective/increase your confidence? (e.g., is there a way NWS/NHC could enhance your decision-making process?)

7. **Thinking now about roughly 48 hours out up until the threat is over**, what decisions need to be made/actions need to be taken, and how are you involved in those decisions? [*If not already answered*] When do these decisions need to be made? [*For broadcast mets, we could ask: "During this timeframe, what do you show/say to your audience?"] ***Redirect if they focus a lot on the aftermath when forecast info is no longer of interest/useful***

a. Are there any additional decisions you make / actions you take during this timeframe? And when do they need to be made? [*no matter how small the decision(s)*]

b. What forecast information do you find most useful during this timeframe and what are you looking for?

c. From whom/what organizations do you obtain this information? How? (*Prompt for information from different NWS entities, e.g., NHC, local forecast office, other centers, and commercial services*)

d. Do you have suggestions for how this information could be improved to fit your decision-making needs? Is this information available when you need it? (*Prompt for kinds of forecast information they typically want to have and what they look for in the information (e.g., rates, amounts, update frequency, uncertainty information).*)

e. [*If not already answered*] Is there additional forecast information that you'd like to have during this timeframe? That would make your decisions easier/more effective/increase your confidence? (e.g., is there a way NWS/NHC could enhance your decision-making process?)

8. Are there exceptions to the typical tropical cyclone threat decision/action timeline that you discussed? For instance, are there situations that comes to mind in which the "typical" evolution of decisions or actions you described did not apply, or when you use different types of forecast information? Please explain.

9. [*If not already answered*] I want to follow up about how the decisions you make / actions you take might involve information for *specific* hazards related to a tropical cyclone. Do you use any forecast information or tools that are specific to different types of hazards that may be produced by a tropical cyclone, such as extreme winds, storm surge, heavy rainfall and inland flooding, rough surf and rip currents, and/or tornadoes?

    a. If yes, what forecast information, products, or tools come to mind?

    b. If yes, tell me about (each). How do you use (this/these) to make decisions?

10. Are there individuals or communities in your region that are particularly vulnerable to TC threats? If yes, please explain.

    a. Are there specific decisions you need to make or actions you need to take related to these individuals or communities in the context of a TC threat? [*Prompt: Are there specific ways you need to plan, prepare for, or effectively communicate with these communities during a TC threat?*]

    b. Is there specific information you use or would like to have in order to make these decisions/take these actions? [*Prompt: For example, are there any specific TC forecast products you use or would like to have that would help in making these decisions/taking these actions?*]

Now we would like to focus specifically on uncertainties and inconsistencies in forecast information and decision making.

11. Are there particular aspects of decision making about tropical cyclones that tend to be trickier than others? What are these and why? *[Prompt specifically for decisions related to forecast information/products and how previous decisions enable or constrain subsequent ones.]*

12. If you receive unclear, uncertain, or inconsistent forecast information for the decision(s) you need to make/actions you need to take, what do you do? *[Prompt: How do you work with this information to make decisions?]*

III. PRODUCT-SPECIFIC QUESTIONS

In the final part of this interview, we will be asking you about different types of forecast products - some of which may have already been mentioned. We are especially interested in understanding how useful and applicable the collection of current products is for your decision-making needs, and how the forecast information currently available could be improved.

13. Looking at this set of tropical cyclone products, which ones have information that you use? [*And as you are going through these products, please sort them in order of how frequently you use the information in the products, from most frequently to least frequently/not at all.]*

    a. Cone of Uncertainty _________

    b. Tropical Cyclone Wind Speed Probabilities ___________

    c. Time of Arrival of Tropical Storm Force Winds Graphic _________

    d. Tropical Storm or Hurricane Watch/Warning __________

    e. Storm Surge Watch/Warning ___________

    f. Storm Surge Inundation Graphics (e.g., Potential Storm Surge Flooding)

    g. NHC or Local Weather Forecast Office (WFO) Key Messages _________

    h. Hurricane Local Statements (HLS) ___________

    i. Hurricane Threats and Impacts (HTI) Graphics __________

    j. Rainfall/inland flooding inundation (e.g., WPC Excessive Rainfall Outlook) *[do you use this or a similar product(s)?]* _______________

    k. Five-Day Graphical Tropical Weather Outlook

    l. SPC Convective Outlook _______________

For products they do use:

14. In thinking about the most commonly used forecast products, can you explain to me in a bit more detail why these are useful for your work? (Prompt: how do you use this information?)

15. Is there information about TCs that you would like to have that is not provided in the forecast products you use? [*What is that information, and when is it needed? How would you like it to be presented? How could products/information be made more actionable for decision making?]*

For products they do <u>not</u> use/found to be the least useful:

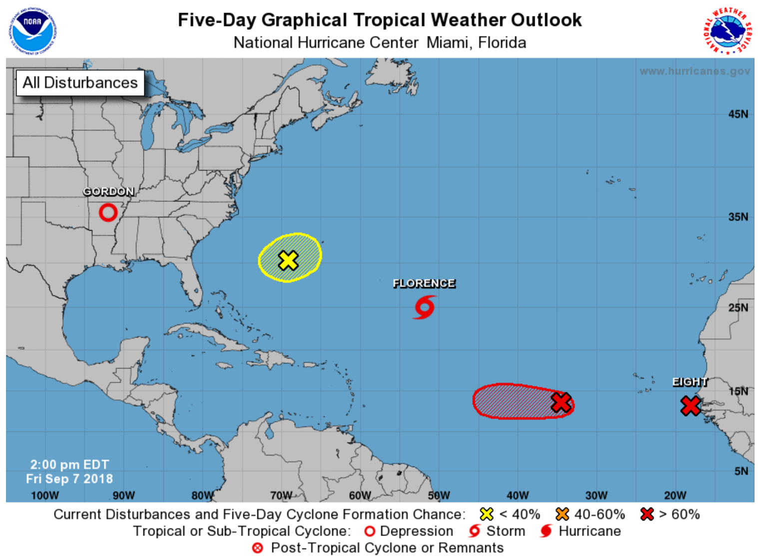
16. For those forecast products you found to be the *least* useful, what elements of these products could be improved? Or do you suggest different products, or different forecast information? What would this look like?

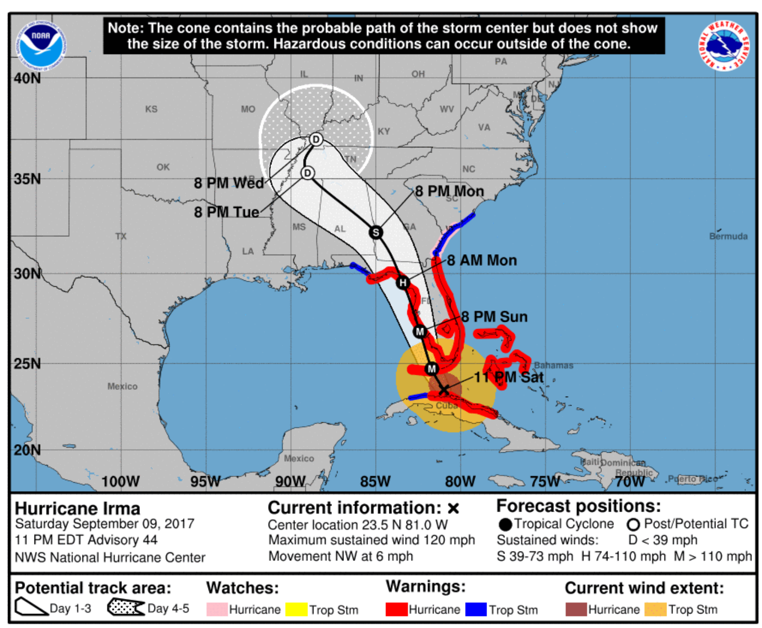
17. [*If they do not use and If not already mentioned*] Are you familiar with these forecast products?

18. To conclude, is there anything else you would like to share about TC-related decision making or about forecast products or information that we haven't discussed?

APPENDIX 2. NWS TC-RELATED PRODUCTS USED IN INTERVIEWS, WITH EXAMPLES

This appendix lists the NWS TC-related products presented to interviewees, as in Figure 1, with example images. Product descriptions and examples were obtained from NOAA via noaa.gov, weather.gov, and NOAA collaborators.

<table>
<tr><th>Tropical Cyclone (TC) Product</th><th>Example</th></tr>
<tr><td>Graphical Tropical Weather Outlook: Map depicting the TC formation potential of current and future tropical disturbances during the next 2 or 5 days. Provided by: NWS National Hurricane Center.</td><td>


</td></tr>
<tr><td>Track Forecast Cone (“Cone of Uncertainty”): Map depicting the probable track of the center of a TC during the next 5 days, along with its forecasted intensity, watches/ warnings, initial TC wind field (if selected), and other information. Provided by: NWS National Hurricane Center.</td><td>


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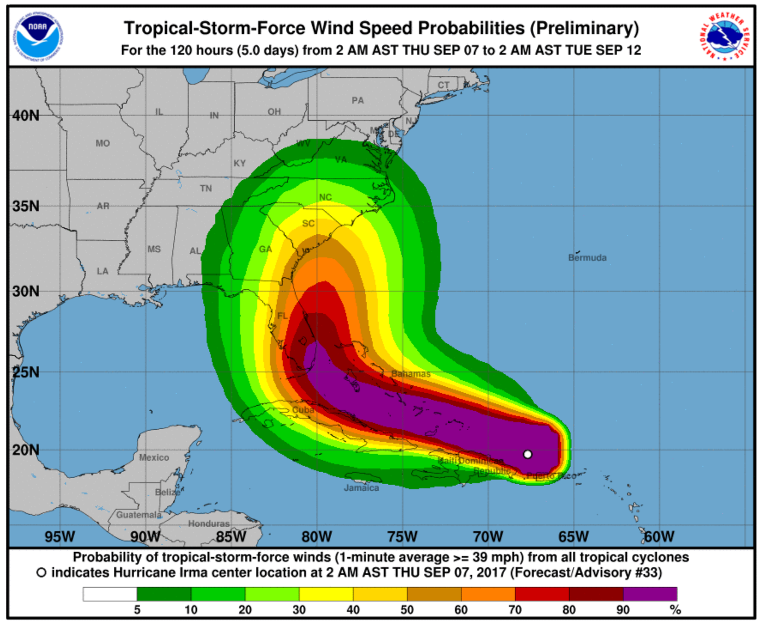
<table>
<tr><th>Tropical Cyclone (TC) Product</th><th>Example</th></tr>
<tr><td>Tropical Cyclone Wind Speed Probabilities Graphic: Map depicting the probabilities of sustained surface (10-m elevation) wind speeds of at least 39 mph (tropical storm), 58 mph, or 74 mph (hurricane) at different locations during the next 5 days; 39 mph example shown. Provided by: NWS National Hurricane Center.</td><td>
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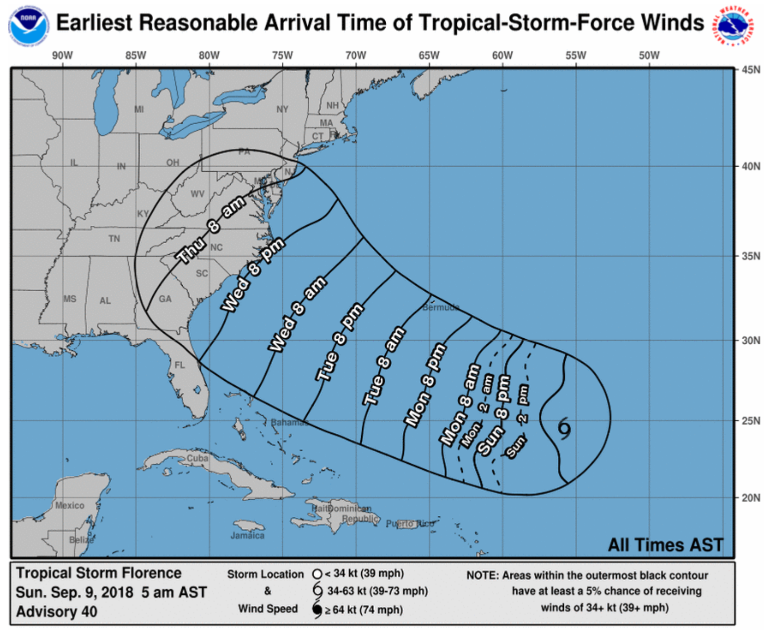
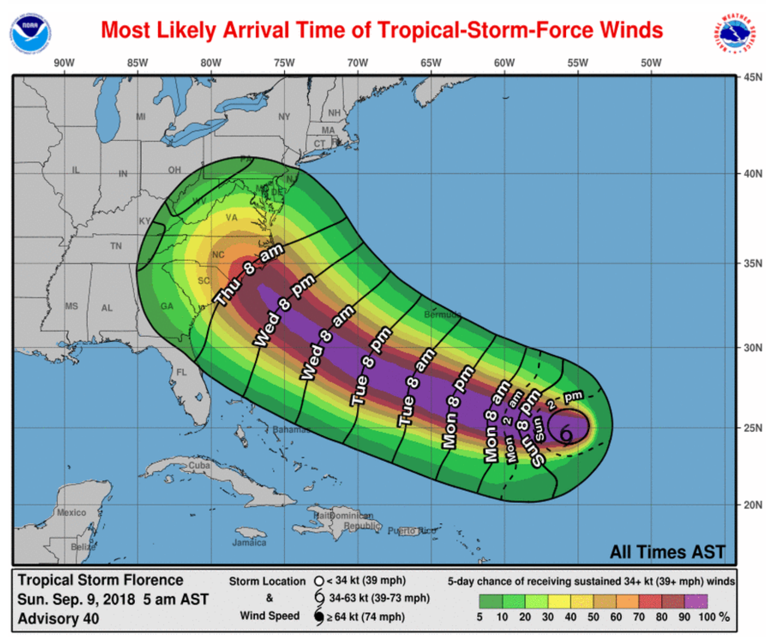
<table>
<tr><th>Tropical Cyclone (TC) Product</th><th>Example</th></tr>
<tr><td>Arrival of Tropical-Storm-Force Winds Graphic: Earliest Reasonable Arrival Time: Map depicting the time before which there is a 10% or less chance of seeing the onset of sustained tropical-storm-force winds at different locations during the next 5 days; Most Likely Arrival Time: Map depicting the time before or after which the onset of tropical-storm-force winds is equally likely at different locations during the next 5 days. Provided by: NWS National Hurricane Center.</td><td>




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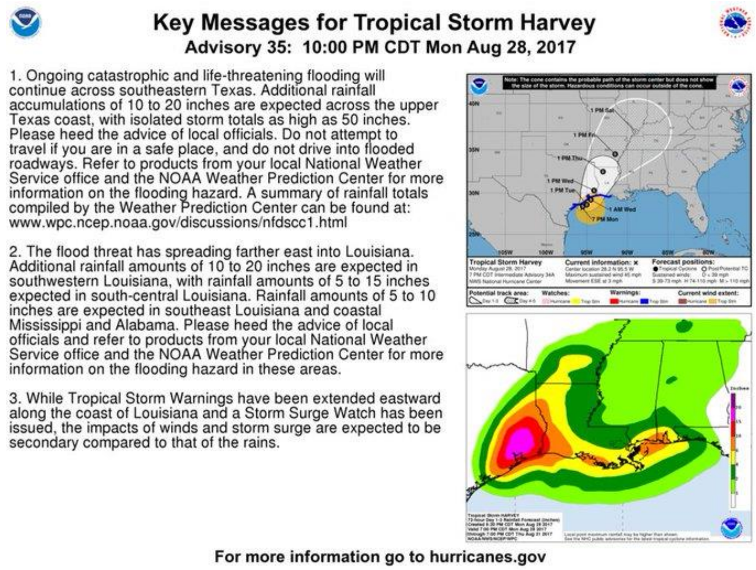
</table>

<table>
<tr><th>Tropical Cyclone (TC) Product</th><th>Example</th></tr>
<tr><td>Key Messages Graphic: Graphic with text highlighting essential points about hazards and forecast uncertainty for a TC, along with relevant NWS graphical TC products. Provided by: NWS National Hurricane Center.</td><td>
</td></tr>
<tr><td>Tropical Cyclone Public Advisory: Text product containing a list of all current watches and warnings for a TC, along with the storm's position, current motion, intensity, and other information; example shown is truncated. Provided by: NWS National Hurricane Center.</td><td>ZCZC MIATCPAT3 ALL
TTAA00 KNHC DDHHMM

BULLETIN
HURRICANE SANDY ADVISORY NUMBER 19
NWS NATIONAL HURRICANE CENTER MIAMI FL AL182012
1100 PM EDT FRI OCT 26 2012

...SANDY REMAINS A HURRICANE AS IT MOVES SLOWLY NORTHWARD AWAY FROM THE BAHAMAS...

SUMMARY OF 1100 PM EDT...0300 UTC...INFORMATION

LOCATION...27.7N 77.1W
ABOUT 90 MI...145 KM N OF GREAT ABACO ISLAND
ABOUT 395 MI...630 KM SSE OF CHARLESTON SOUTH CAROLINA
MAXIMUM SUSTAINED WINDS...75 MPH...120 KM/H
PRESENT MOVEMENT...N OR 10 DEGREES AT 7 MPH...11 KM/H
MINIMUM CENTRAL PRESSURE...969 MB...28.61 INCHES

WATCHES AND WARNINGS

CHANGES WITH THIS ADVISORY...

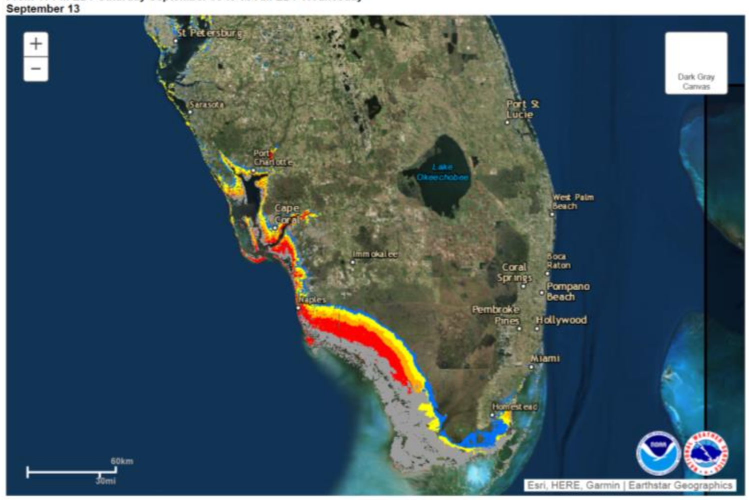
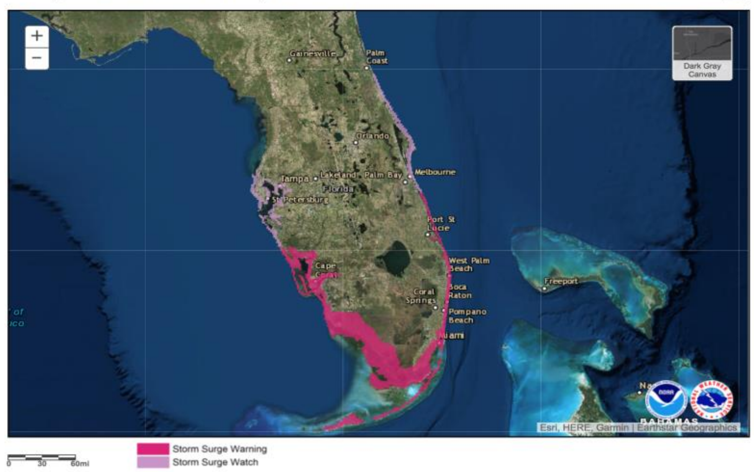
NONE.

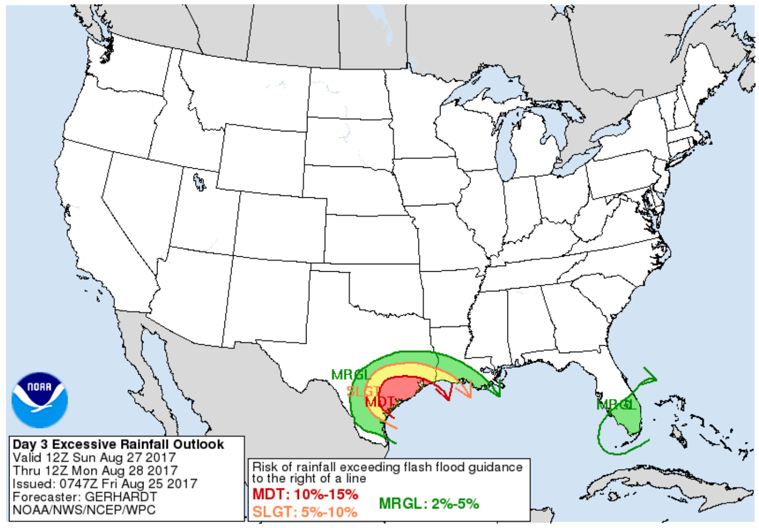
SUMMARY OF WATCHES AND WARNINGS IN EFFECT...

A TROPICAL STORM WARNING IS IN EFFECT FOR...
* FLORIDA EAST COAST FROM NORTH OF JUPITER INLET TO ST AUGUSTINE
* SOUTH SANTEE RIVER TO DUCK...INCLUDING PAMLICO AND ALBEMARLE SOUNDS
* GREAT ABACO AND GRAND BAHAMA ISLANDS

A TROPICAL STORM WATCH IS IN EFFECT FOR...
* SAVANNAH RIVER TO SOUTH SANTEE RIVER
* FLORIDA EAST COAST FROM NORTH OF ST AUGUSTINE TO FERNANDINA BEACH
* BERMUDA

IN ADDITION...GALE WATCHES ARE IN EFFECT FOR AREAS NORTH OF THE TROPICAL STORM WARNING AREA. SEE STATEMENTS FROM LOCAL NATIONAL WEATHER SERVICE FORECAST OFFICES.</td></tr>
</table>

Tropical Cyclone (TC) Product	Example
Potential Storm Surge Flooding Map: Map depicting the risk of coastal flooding from storm surge at different normally-dry land locations, represented by a "reasonable worst–case scenario" in which there is approximately a 10% chance that storm surge flooding at any particular location could be higher than the values shown on the map; issued when onset of tropical-storm-force winds is anticipated along the U.S. coast within 48 hours. Provided by: NWS National Hurricane Center.	**Potential Storm Surge Flooding Map (Inundation)** **NHC Potential Storm Surge Flooding Map** **Hurricane IRMA (2017) Advisory 44** **From 11 PM EDT Saturday September 09 to 05 AM EDT Wednesday September 13** 
Storm Surge Watch/Warning Graphic: Map depicting areas along the U.S. coast where there is a possibility (watch) or danger (warning) of life-threatening storm surge from a TC or other storm in the next 48 or 36 hours, respectively. Provided by: NWS National Hurricane Center.	**Storm Surge Watch/Warning Graphic*** **Hurricane Irma** **Advisory 039 Issued: 5:00 PM EDT Fri Sep 8** 

<table>
<tr><th>Tropical Cyclone (TC) Product</th><th>Example</th></tr>
<tr><td>Excessive Rainfall Outlook Graphic: National map depicting the risk of potentially flooding rainfall at different locations during the time indicated (e.g., Day 1, Day 2, Day 3), represented by the probability that rainfall will exceed flash flood guidance within 40 km of a point. Provided by: NWS Weather Prediction Center.</td><td>
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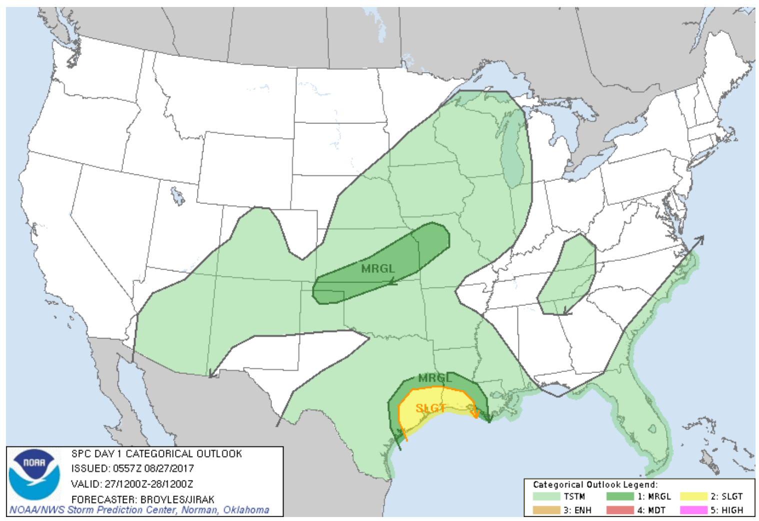
<tr><td>Convective Outlook Graphic: National map depicting the risk of severe convective weather at different locations during the time indicated (e.g., Day 1, Day 2, Day 3), represented by the probability that a severe weather event will occur within 40 km of a point. Provided by: NWS Storm Prediction Center.</td><td>
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</table>

<table>
<tr><th>Tropical Cyclone (TC) Product</th><th>Example</th></tr>
<tr><td>Hurricane Local Statement: Text product containing essential information about a TC for a local area, including information about the current storm, local watches/warnings in effect, potential local hazardous conditions and impacts, and any actions declared by local emergency managers; example shown is truncated. Provided by: NWS Weather Forecast Offices.</td><td>000
WTUS84 KHGX 251530
HLSHGX
TXZ163-164-176>179-195>200-210>214-226-227-235>238-252330-

Hurricane Harvey Local Statement Advisory Number 21
National Weather Service Houston/Galveston TX AL092017
1030 AM CDT Fri Aug 25 2017

This product covers Southeast Texas

OUTER RAINBAND FROM HARVEY SWIPING THE LOWER AND MIDDLE TEXAS COASTS

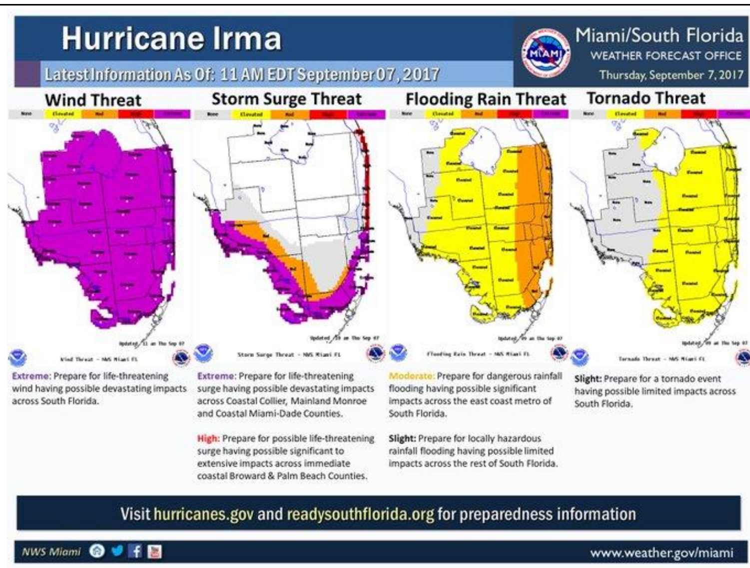
NEW INFORMATION
----

* CHANGES TO WATCHES AND WARNINGS:
    - None

* CURRENT WATCHES AND WARNINGS:
    - A Tropical Storm Warning and Storm Surge Watch are in effect for Chambers and Harris
    - A Tropical Storm Warning is in effect for Austin, Colorado, Fort Bend, Liberty, Waller, and Wharton
    - A Storm Surge Warning and Hurricane Warning are in effect for Jackson and Matagorda
    - A Storm Surge Warning and Tropical Storm Warning are in effect for Brazoria and Galveston

* STORM INFORMATION:
    - About 190 miles south-southwest of Galveston TX or about 120 miles south-southeast of Port O'Connor TX
    - 26.7N 96.0W
    - Storm Intensity 110 mph
    - Movement Northwest or 315 degrees at 10 mph

SITUATION OVERVIEW

Harvey continues to move northwest late this morning and remains a high-end category 2 hurricane with maximum sustained winds of 110 mph. Harvey is forecast to continue strengthening and will most likely become a major hurricane today before it makes landfall along the Middle Texas Coast later tonight. The primary impact from Harvey</td></tr>
<tr><td>Hurricane Threats and Impacts Graphics: Set of regional maps depicting the risk of hazardous wind, storm surge, flooding rain, and tornadoes associated with a TC at different locations, issued within 48 hours of anticipated impacts in the region; one of two examples presented to interviewees is shown. Provided by: NWS Weather Forecast Offices.</td><td>
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APPENDIX 3. CODING SCHEME AND INTER-CODER RELIABILITY RESULTS

This Appendix contains the full coding scheme and inter-coder reliability results, calculated as discussed in section 3.3. Indentations indicate sub-codes, and most codes are listed alphabetically within each level of the hierarchy and grouping. Unless indicated with {BR} for broadcast meteorologist or {EM} for emergency manager, all codes were applicable to both types of interviewees. Cohen's kappa is marked NA for latent and miscellaneous codes, and it is italicized for codes that were used five or fewer times in the transcripts used to calculate inter-coder reliability. One code (FEMA) was added after inter-coder reliability was assessed.

Code	**Cohen's kappa**
At-risk populations	0.81
Decisions & actions	0.85
Challenging decisions	NA
Coordination & communication (non-evacuation)	0.80
Evacuation {EM}	0.95
Evacuation of at-risk groups or facilities	0.80
Evacuation coordination & communication	0.53
General population evacuation	*0.80*
Triggers/influences for evacuation decisions	NA
Media coverage {BR}	0.73
Wall-to-wall	1
Organizational preparation/planning decisions	*0.41*
Keeping staff safe	*0*
Staffing decisions	0.5
EOC activation/activities {EM}	0.82
Reporter deployment to different locations {BR}	0.66
Triggers/influences for non-evacuation decisions	NA
Forecast and other meteorological information	0.93
Forecast information sources & channels	0.94
FEMA	added after ICR
Local NWS offices	0.9
NHC	0.93
NWS Chat	*1*
One-on-one forecast conversations	0.53
Other NWS (SPC, WPC, National Water Center, etc.)	0.93
Private meteorology companies	0.86
Most useful forecast info	NA
Other meteorological / forecast info	0.96
Computer models	1
Observational data	*0.5*
Problems with forecasts or products	NA

Code	Cohen's kappa
Suggested improvements to forecasts or products	0.87
TC products	0.78
Advisories	*0*
Cone of Uncertainty	0.90
Forecast Discussion	1
HLS (Hurricane Local Statement)	*0.83*
HTI (Hurricane Threats and Impacts Graphics)	1
Key Messages	*0.91*
MOMs / MEOWs	*1*
Other products	NA
SPC Outlook	0.85
Storm Surge Inundation Graphic	0.53
Storm Surge Watch / Warning	0.87
TC Outlook	0.54
TC Wind Probabilities	1
Time of Arrival of Tropical-Storm Force Winds	0.82
Tropical Storm or Hurricane Watch / Warning	0.86
WPC Excessive Rainfall Outlook	*1*
Other products	NA
Uncertainty in forecast information received	NA
Job roles	NA
Miscellaneous	NA
Public messaging and decision making	0.81
TC hazards & characteristics	0.81
Intensity	0.75
Other hazards	NA
Rainfall / inland flooding	0.76
Size	*0*
Storm surge / coastal flooding	0.68
Tornadoes	0.84
Track / landfall location	0.78
Winds	0.82
TC time frame	0.74
> 5 days	0.56
5 days to 48 hours	0.73
48 hours to impacts	0.91
Impacts +	*0*